Water for Food
ROBERT B. DAUGHERTY INSTITUTE
at the University of Nebraska

Airborne Mapping of Evapotranspiration
Role of Piloted Systems in the Future

Christopher M.U. Neale

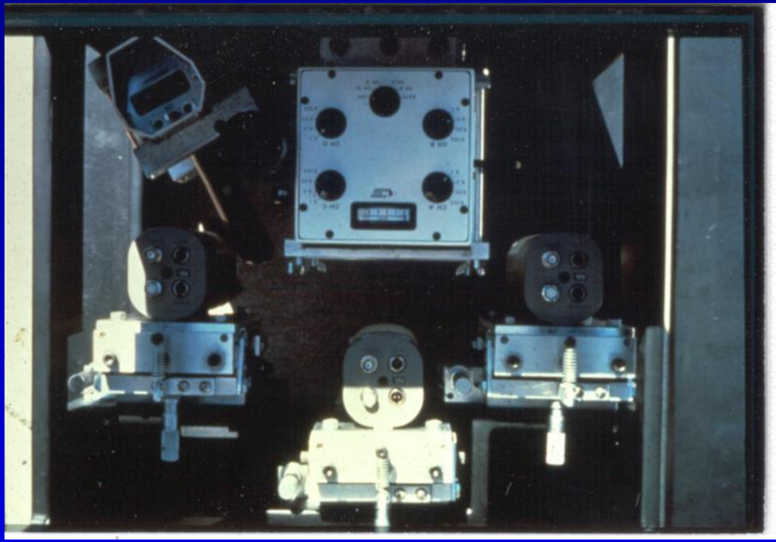
Director of Research

Outline

- Example of a low-cost airborne systems
- Discussion about the niche of these systems
- Description of ET retrieval applications using high-resolution imagery

Evolution of Low-Cost Remote Sensing Technology at USU

USU Multispectral Video/Radiometer System 1990

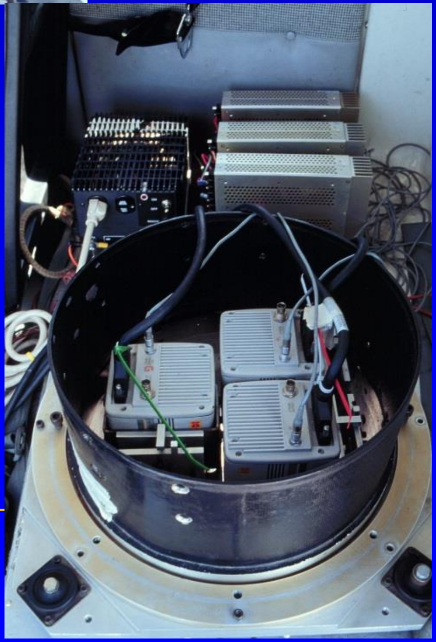


Approximate Cost: < $60,000

Neale, C.M.U. and B.G. Crowther. 1994. Remote Sensing of Environment, Volume: 49 Issue: 3 Pages: 187-194.

USU Airborne Multispectral Digital System 1997

Approximate Cost: < $150,000



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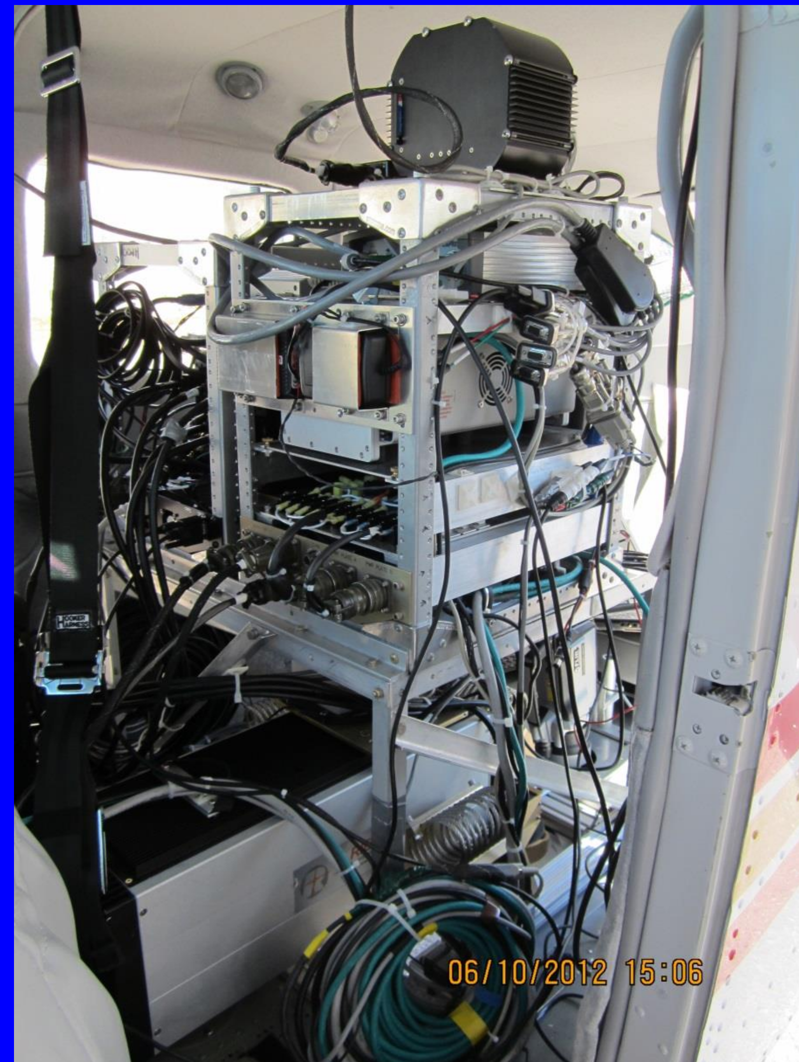
LASSI 560 Airborne Lidar Multi-Sensor System



Approximate Cost: $850,000

- Riegl LPM-Q560 lidar transceiver
- NovAtel SPAN-SE RTK LI/L2 GPS Antenna and Receiver
- Litton LN-200 Inertial Measurement Unit integrated into a NovAtel SPAN interface

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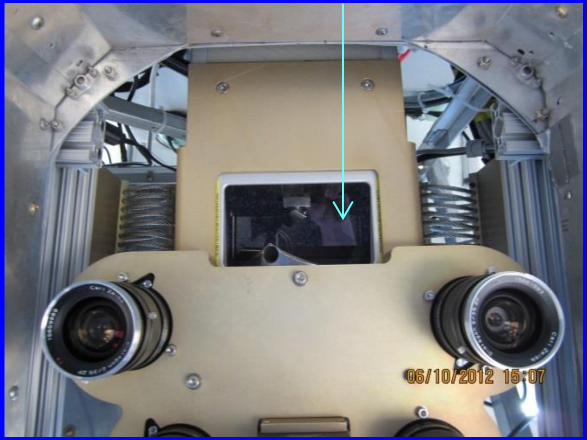
LASSI 560 Airborne Lidar Multi-Sensor System

- Four ImperX Bobcat cameras
- Carl Zeiss 35mm lens on cameras with 55° cross-track FOV
- 4904 x 3280 pixels per camera
- Blue (0.465-0.475 µm), Green (0.545-0.555 µm), Red (0.645-0.655 µm), Near Infrared (NIR) (0.780-0.820 µm), Thermal LWIR 30Hz video

Lidar Window

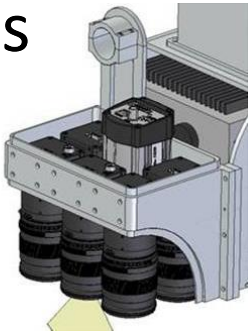


FLIR SC640 TIR Scanner

Details on MS Camera System

- Four co-boresighted multispectral cameras
  - 16 megapixels each for IR, R, G, B bands
  - 64 megapixels total
  - Integrated with lidar
  - Calibrated

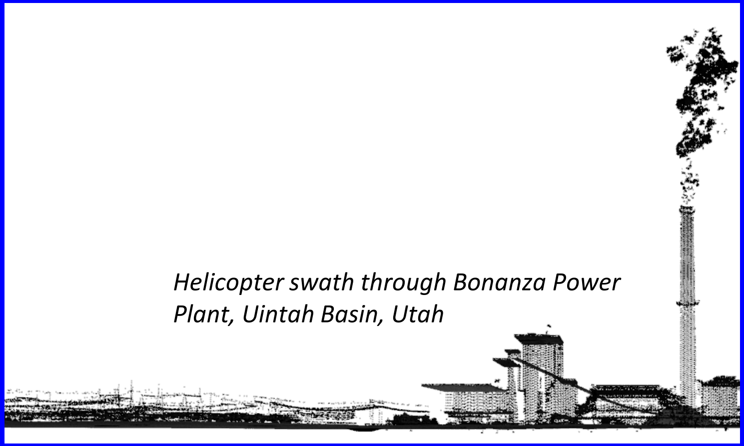
Camera Hardware



Sample of Our Custom 16 mp System
(R,G,B channels shown)

3D Mapping System

– **3D Lidar**
  - **Based on Riegl Q560**
  - **150,000 measurements/second (300 kHz laser)**
  - **25 mm range accuracy at any range**
  - **31 mm footprint @ 1000 m range**
  - **60 degree swath angle**
  - **Integrated with cameras**


Helicopter swath through Bonanza Power Plant, Uintah Basin, Utah

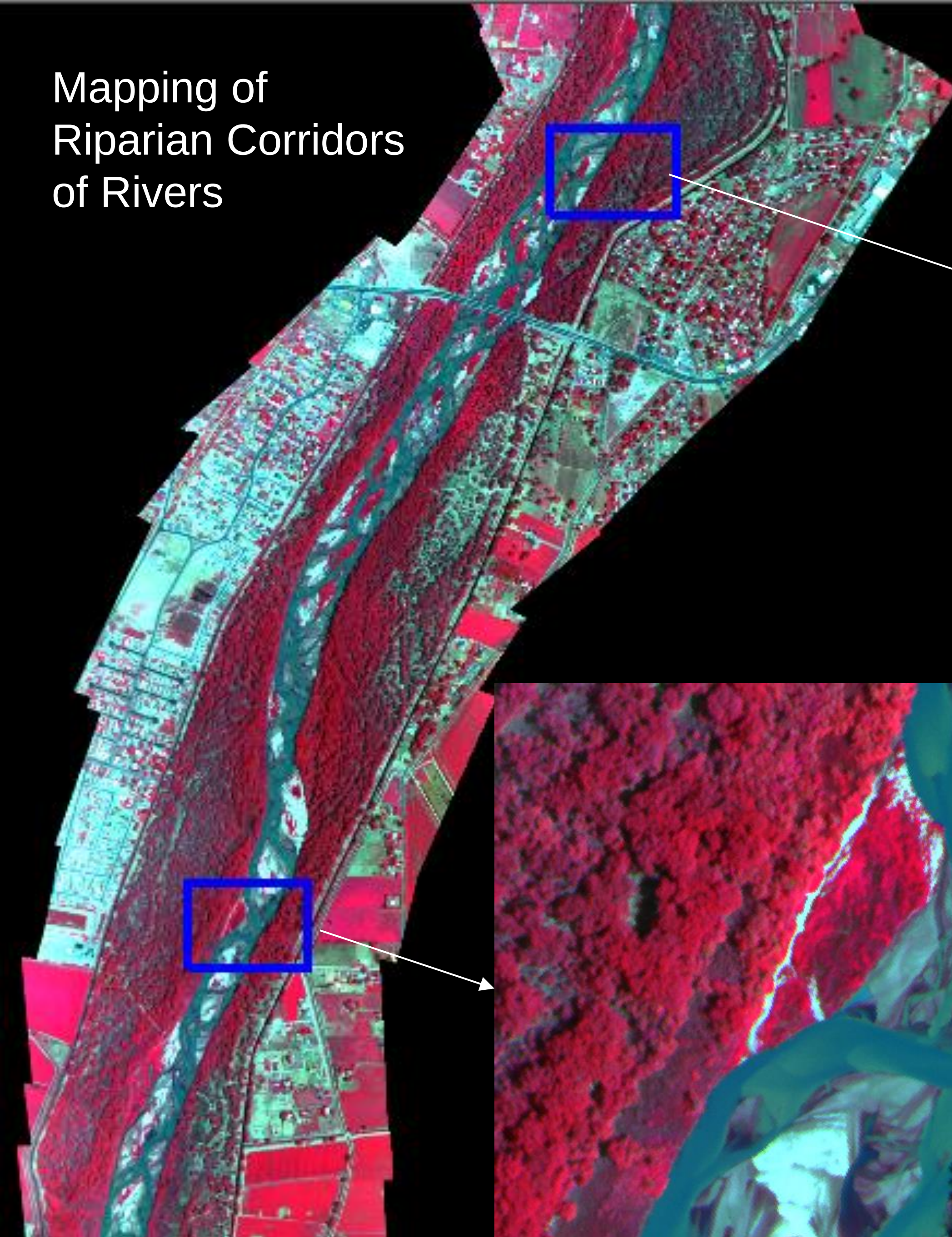

Helicopter swath through Utah State University from 200 m using Riegl Q560 lidar system

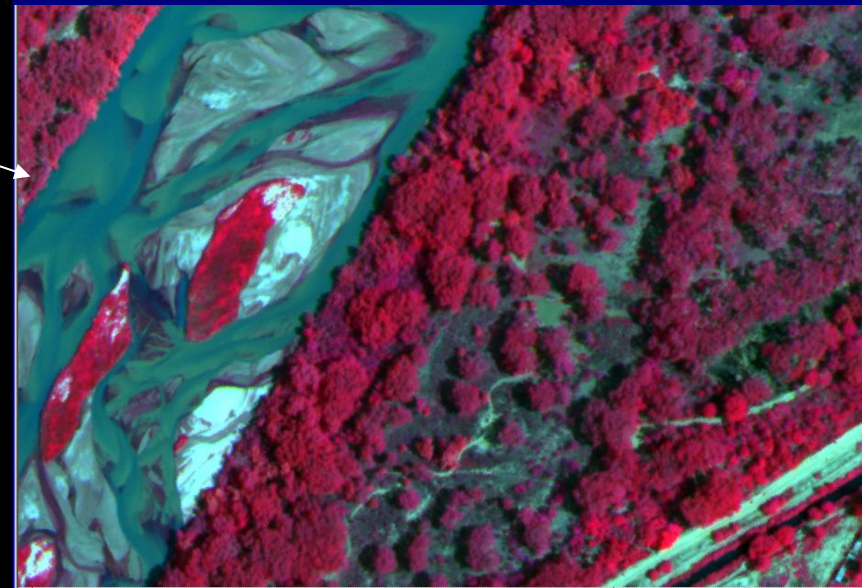
Airborne Systems for Evapotranspiration Monitoring

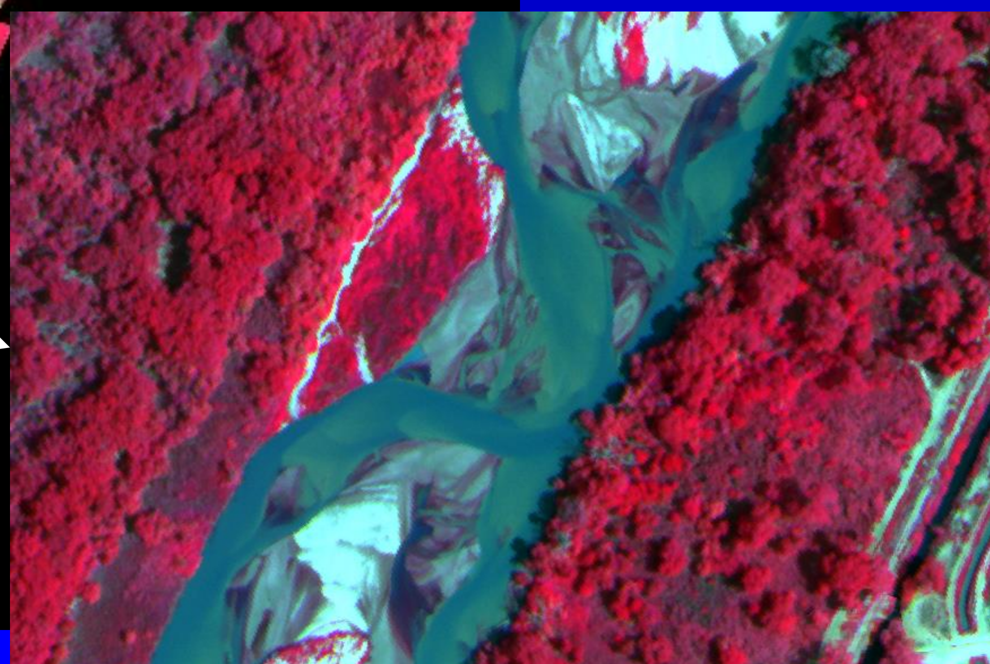
- High spatial resolution imagery (0.1 to 1.5 meters)
- Excellent for mapping surfaces and systems with small scale variability
- Provide an intermediate scale between ground-based ET flux tower measurements and satellite estimates
- Can cover areas up to hundreds of Kilometers cost effectively
- Can acquire data and imagery in a timely manner (subject to weather) to match scientific needs or vegetation phenology
- Costs depend on size of area flown and distance from home base (economy of scale)
- Scientific and monitoring/mapping applications

Urban Areas
Scale: a few meters

Mapping of Riparian Corridors of Rivers

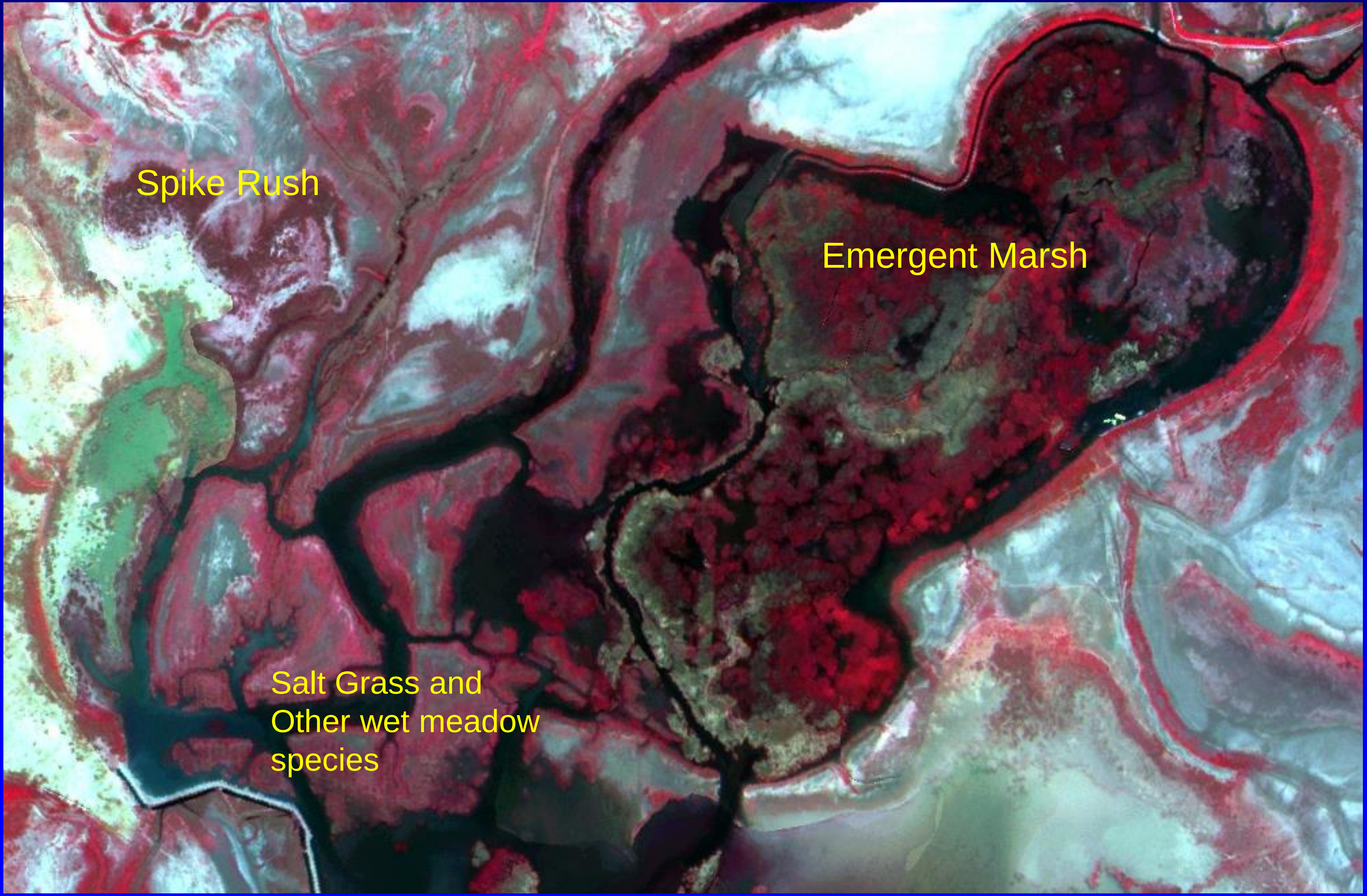






Mapping of Wetlands

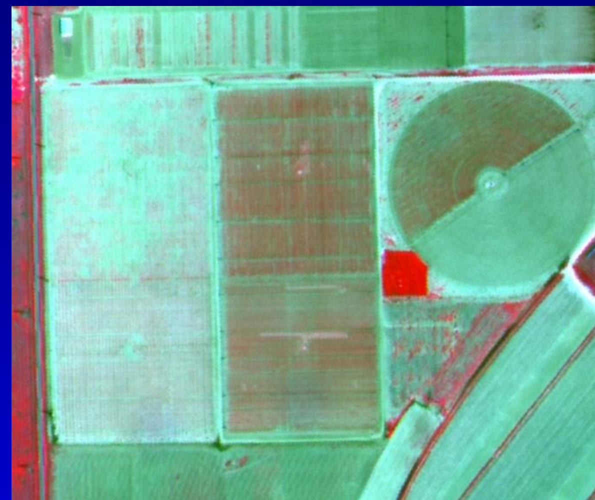
Example of Emergent Marsh & Wet Meadow Habitat



Multitemporal Sequence of Multispectral Images – BEAREX 2008 – Bushland Texas

June 26

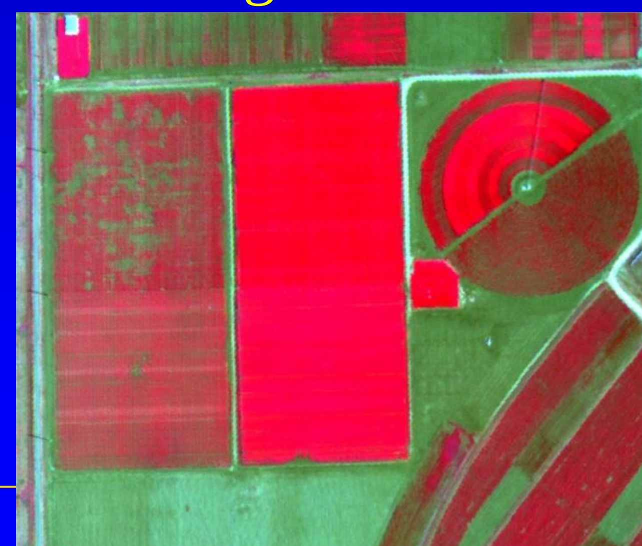
July 12



July 28

August 5

August 13



Type of Product: Lysimeter/Flux Tower Mosaics
Acquired around the satellite overpass time
July 28, 2008

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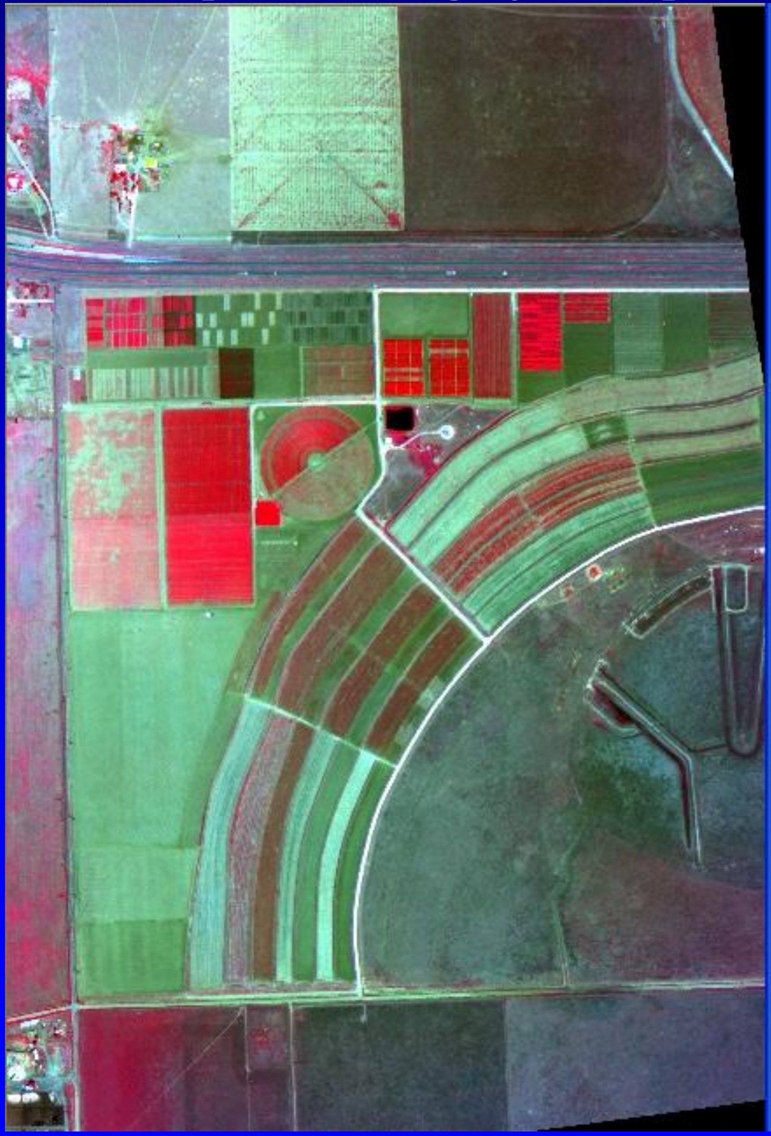
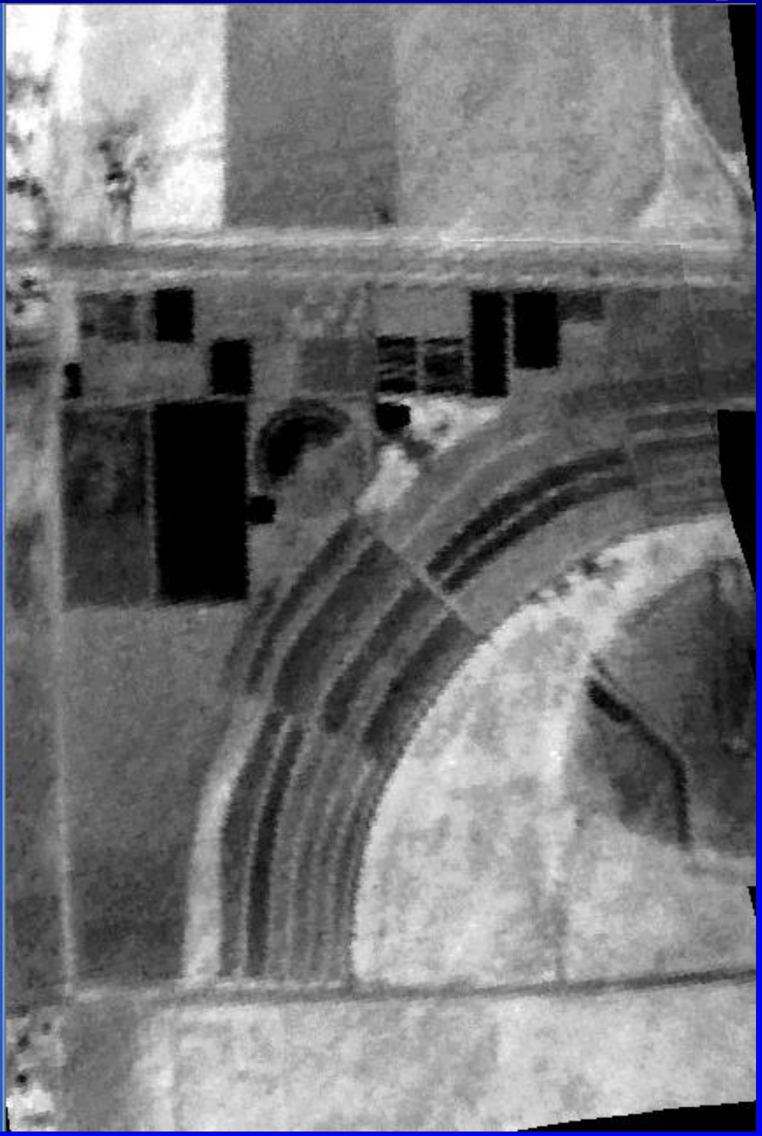
3 Band Multispectral Imagery 1-m pixel

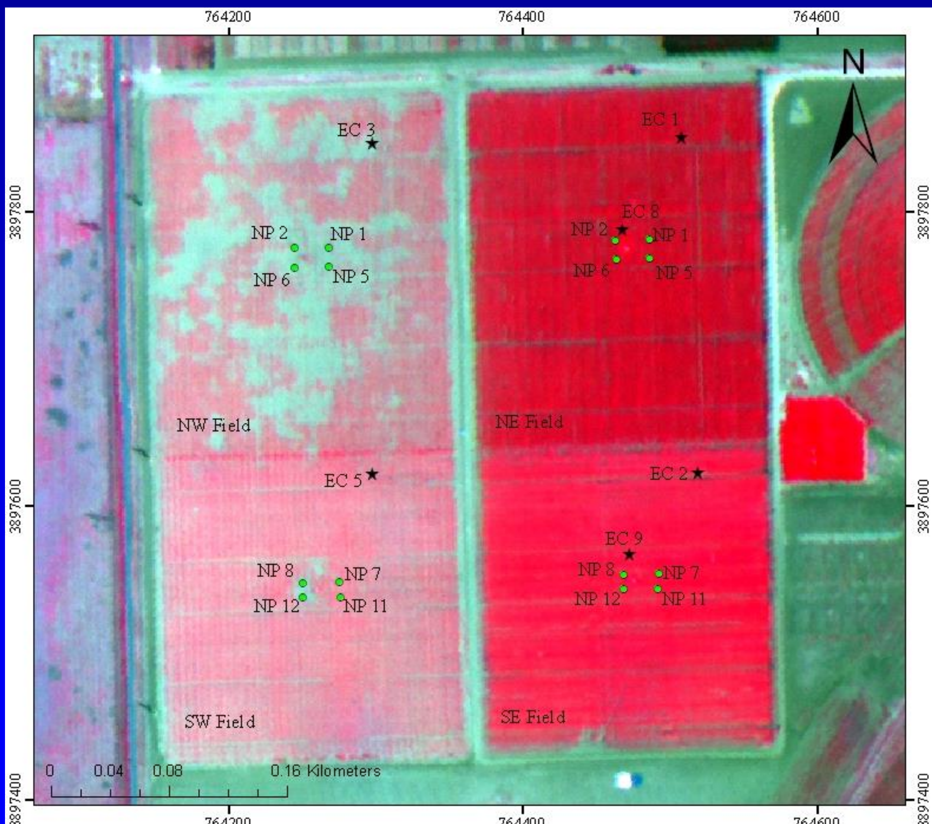


Thermal infrared mosaic 3.5-m pixel

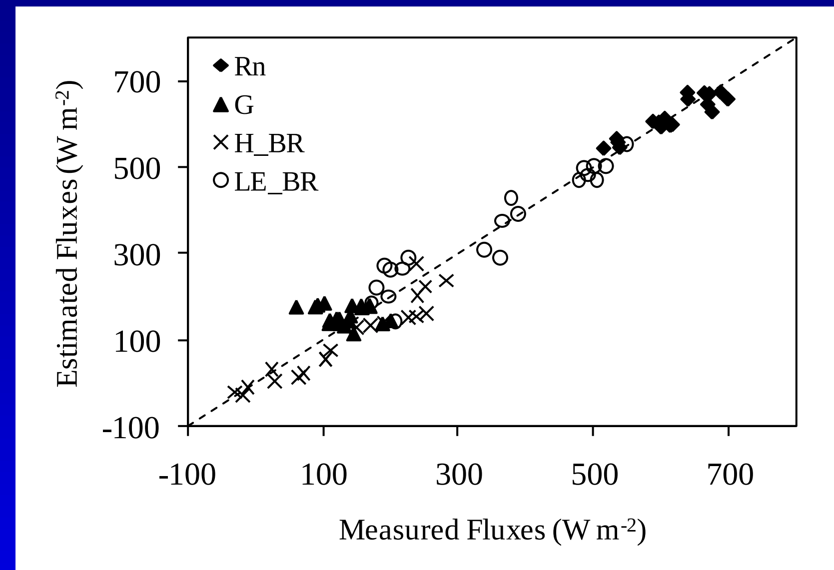


Application of the SETMI Hybrid ET Model
BEAREX 2008 – Bushland Texas
Rain Fed and Irrigated Cotton

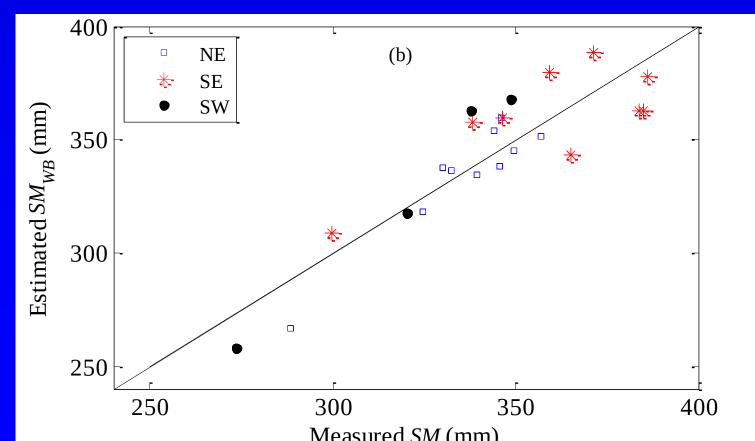
3 Band Multispectral Imagery1-m pixel July 28th, 2008. Green dots: Neutron Probe Access tubes



Comparison of Measured vs Estimated Fluxes



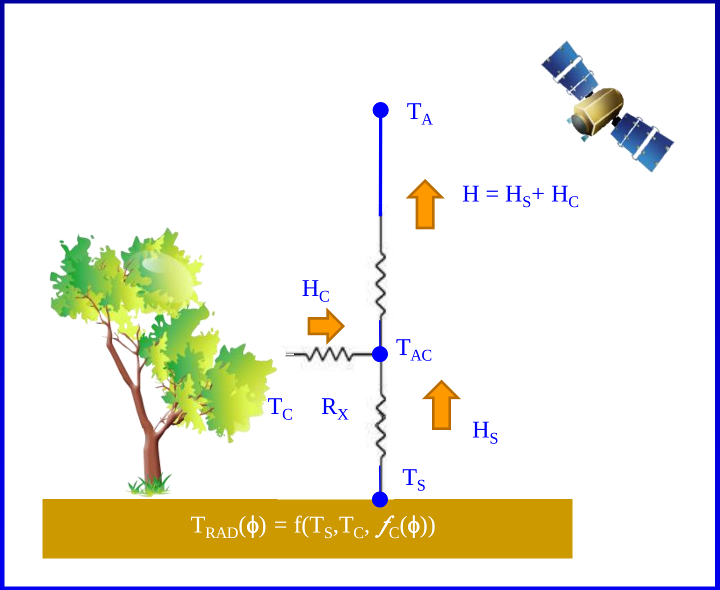
Esimated Soil Moisture vs Measured



Neale, C. M.U., H. M.E. Geli, W. P. Kustas, J. G. Alfieri, P. H. Gowda, S. R. Evett, J.H. Prueger, L. E. Hipps, W. P. Dulaney, J. L. Chávez, A. N. French, T. A. Howell. 2012. Soil water content estimation using a remote sensing based hybrid evapotranspiration modeling approach. Advances in Water Resources, Volume 50, December 2012, Pages 152-161

The Hybrid ET model[1]

Diagnostic SVAT Scheme
The Two-Source Energy Balance Model (TSEB)[2,3]

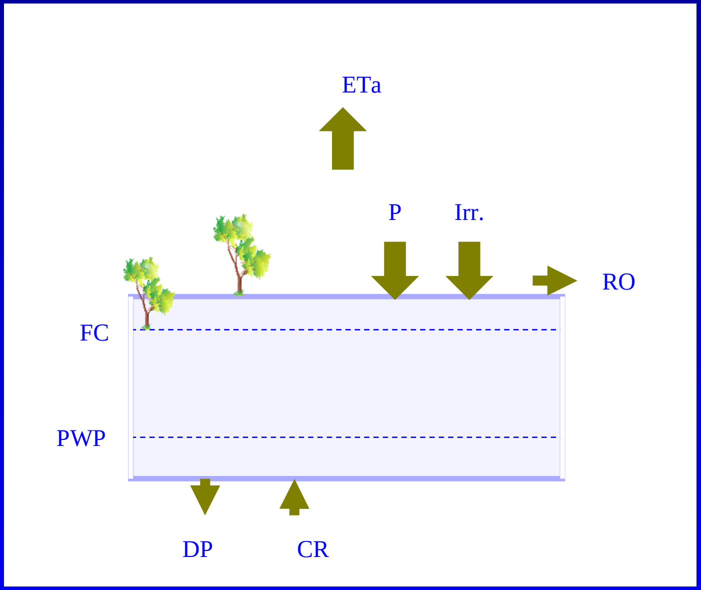


Series Resistance Formulation

$LE = Rn - G - H$

[2] Norman and Kustas (1995), [3]Li , et al.(2005)

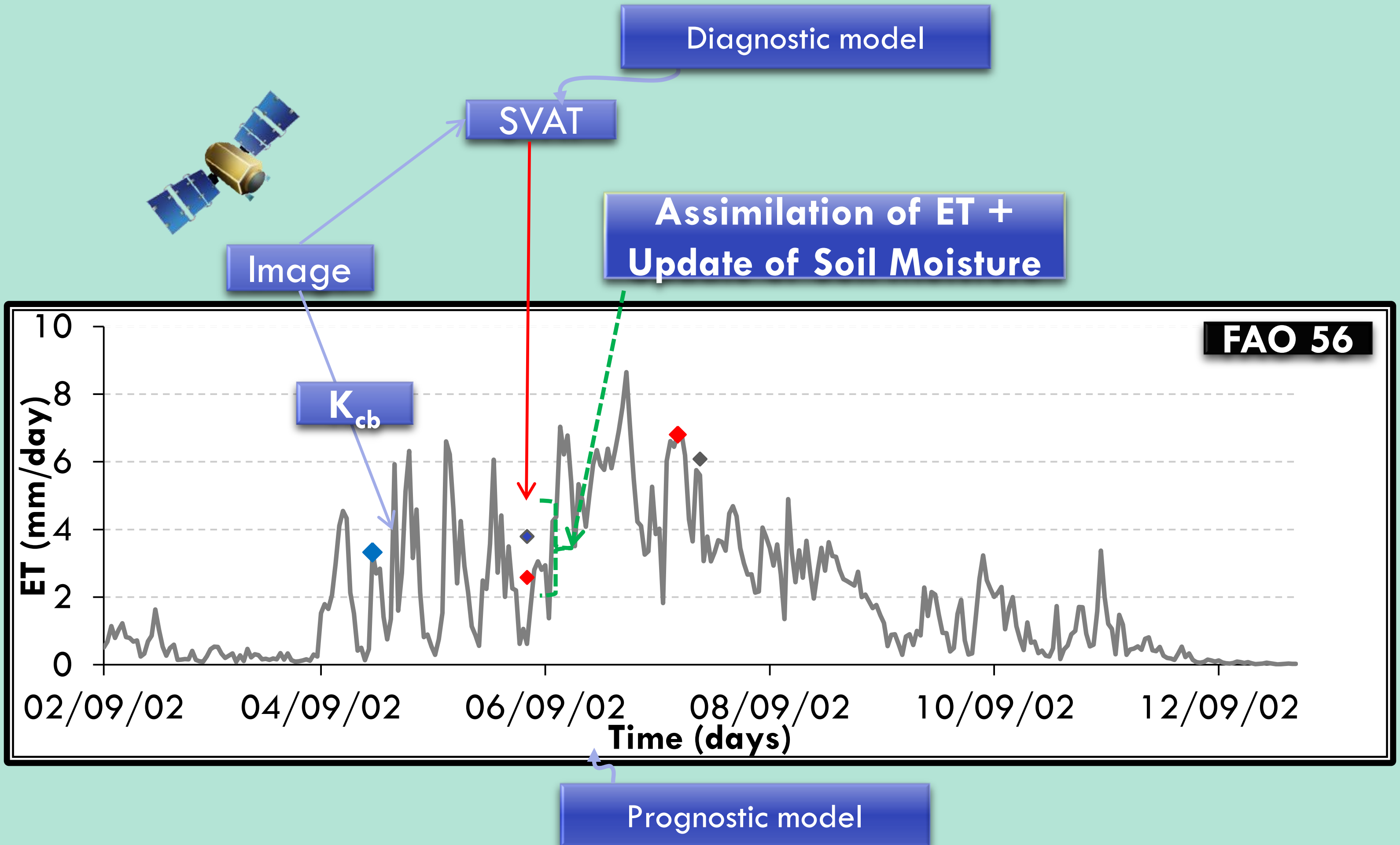
Prognostic
Modified FAO-56[4,5]
water balance of the root zone



Modified with reflectance -based basal crop coefficient (Kcbrf)[5]

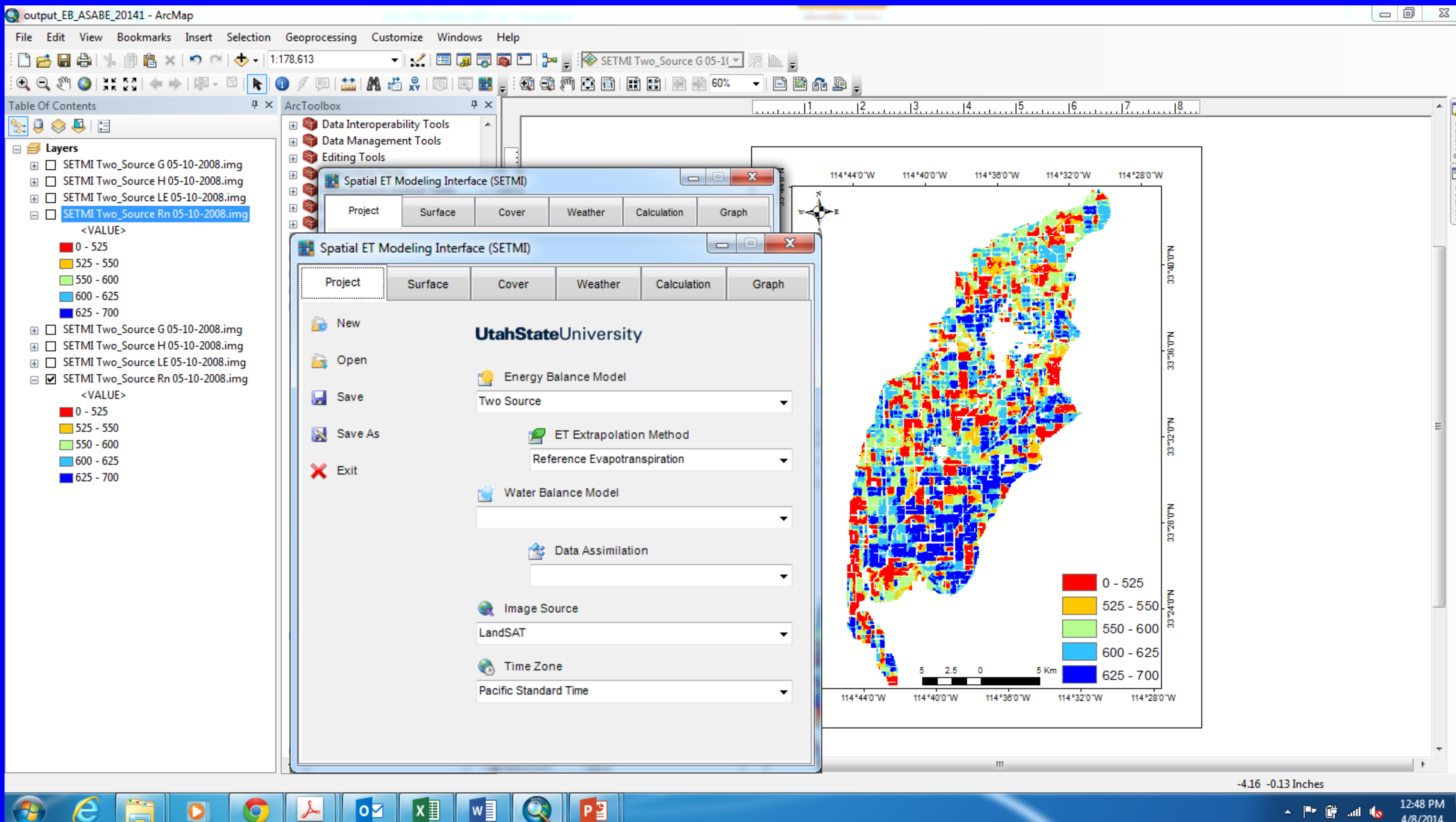
[4] Allen et al. (1998), [5]Neale et al. (1989)

[1]Neale et al. (2012), Soil water content estimation using a remote sensing based hybrid evapotranspiration modeling approach. Advances in Water Resources.



Diagnostic model
SVAT
Assimilation of ET +
Update of Soil Moisture
Image
K_{cb}
FAO 56
ET (mm/day)
0
2
4
6
8
10
02/09/02
04/09/02
06/09/02
08/09/02
10/09/02
12/09/02
Time (days)
Prognostic model

The Spatial ET Modeling Interface (SETMI)[1]



1 Geli, H. M. E. and C.M.U. Neale, (2012), Spatial evapotranspiration modeling (SETMI), Proc. IAHS 352, Remote Sensing and Hydrology (September 2010), ISSN 0144-7815

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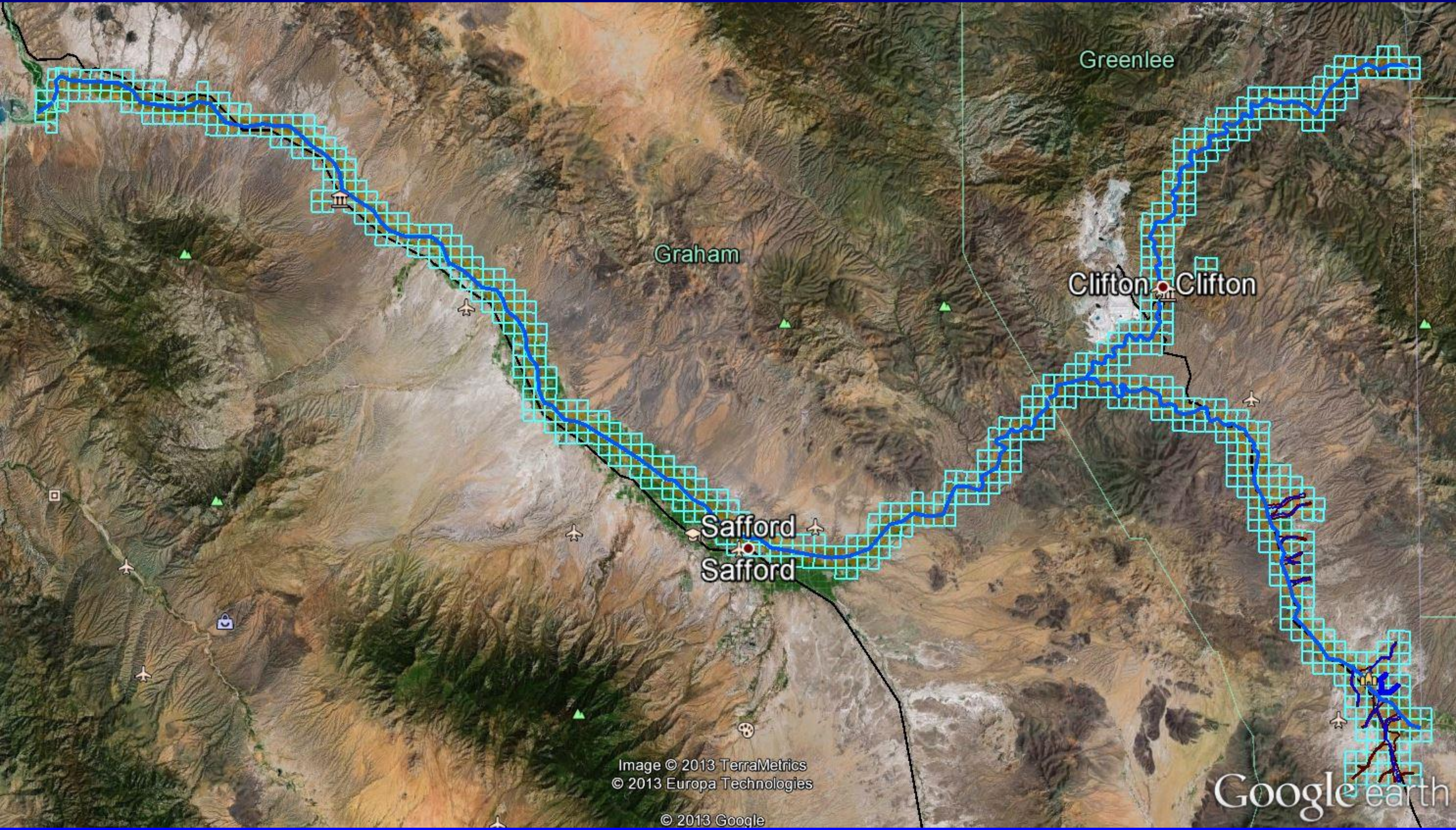
Gila River Flight Coverage and Tile Index



Lidar and Image data delivered in tiles covering 1 km x 1 km area

Products

- Lidar Point Clouds classified into ground surface and vegetation
- Lidar derived products such as Digital Elevation Models at 1-meter grid size
- Natural Color (RGB) and Multispectral (NIR, Red and Green band) ortho-mosaics
- Classified floodplain imagery to obtain natural and invasive vegetation species and other surface types (soil, sand, water …)

Gila River Tile 212
Color and False Color Ortho Mosaic

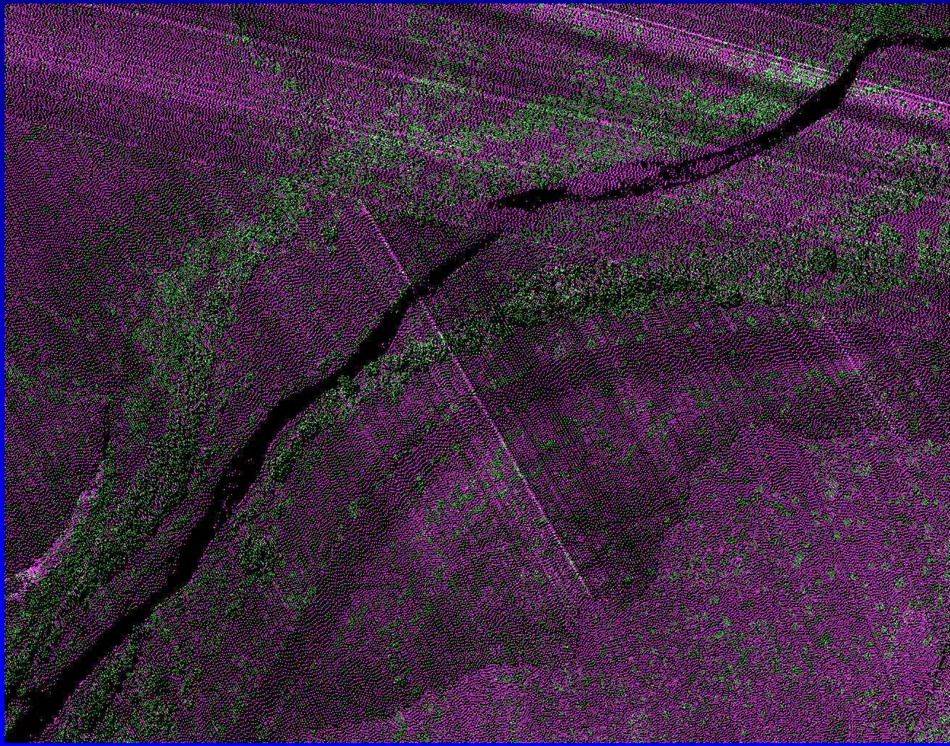
R,G,B

NIR, R, G

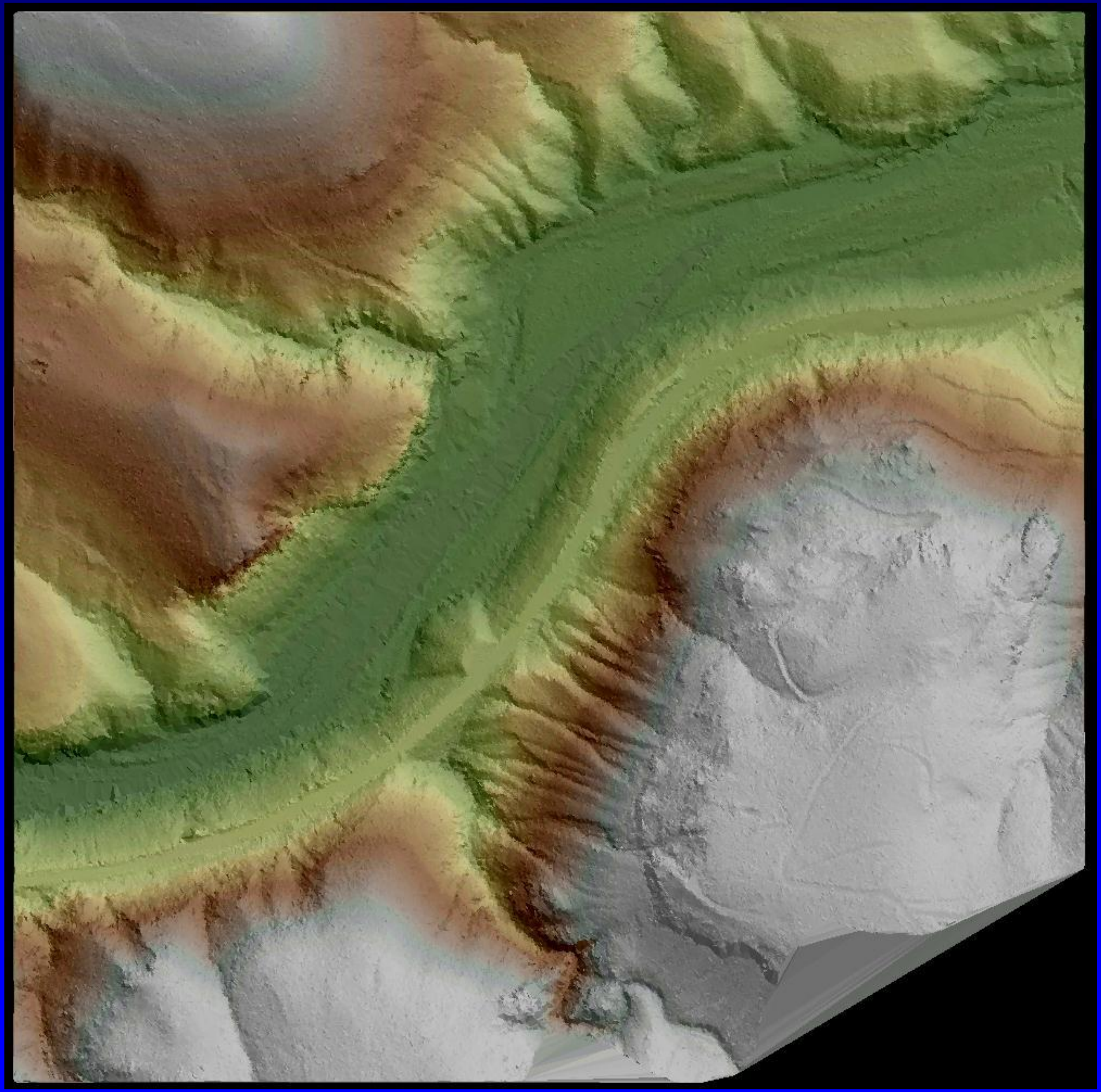
Gila River Lidar Point Cloud Classification
Tile 212

Lidar Intensity of Returns

Classified Point Cloud Vegetation – Non-veg

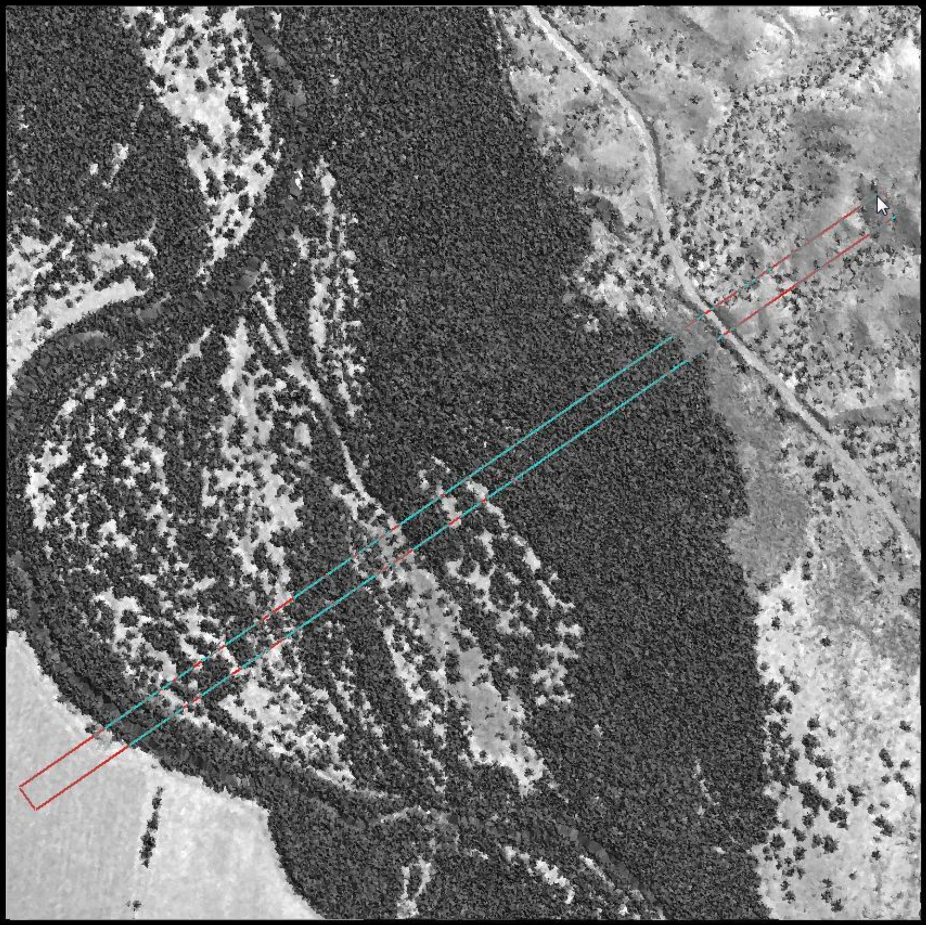


Gila River Tile 212 Surface Model TIN

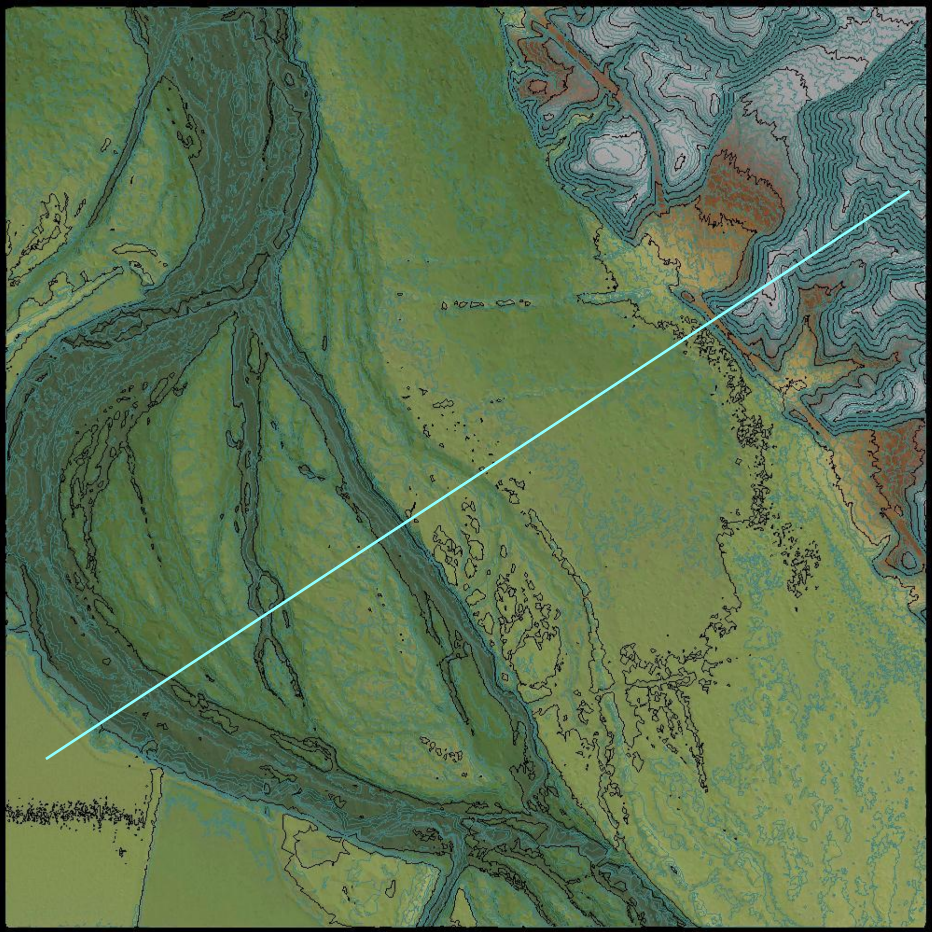


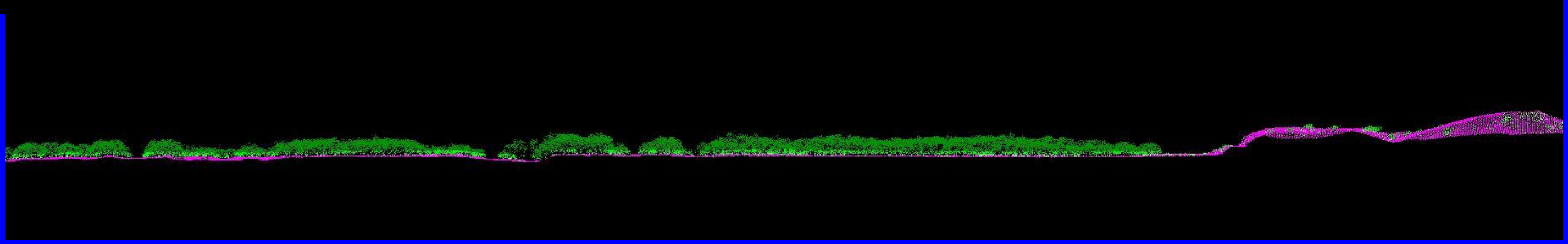
Gila River Tile 247

Point Cloud Intensity Cross-section



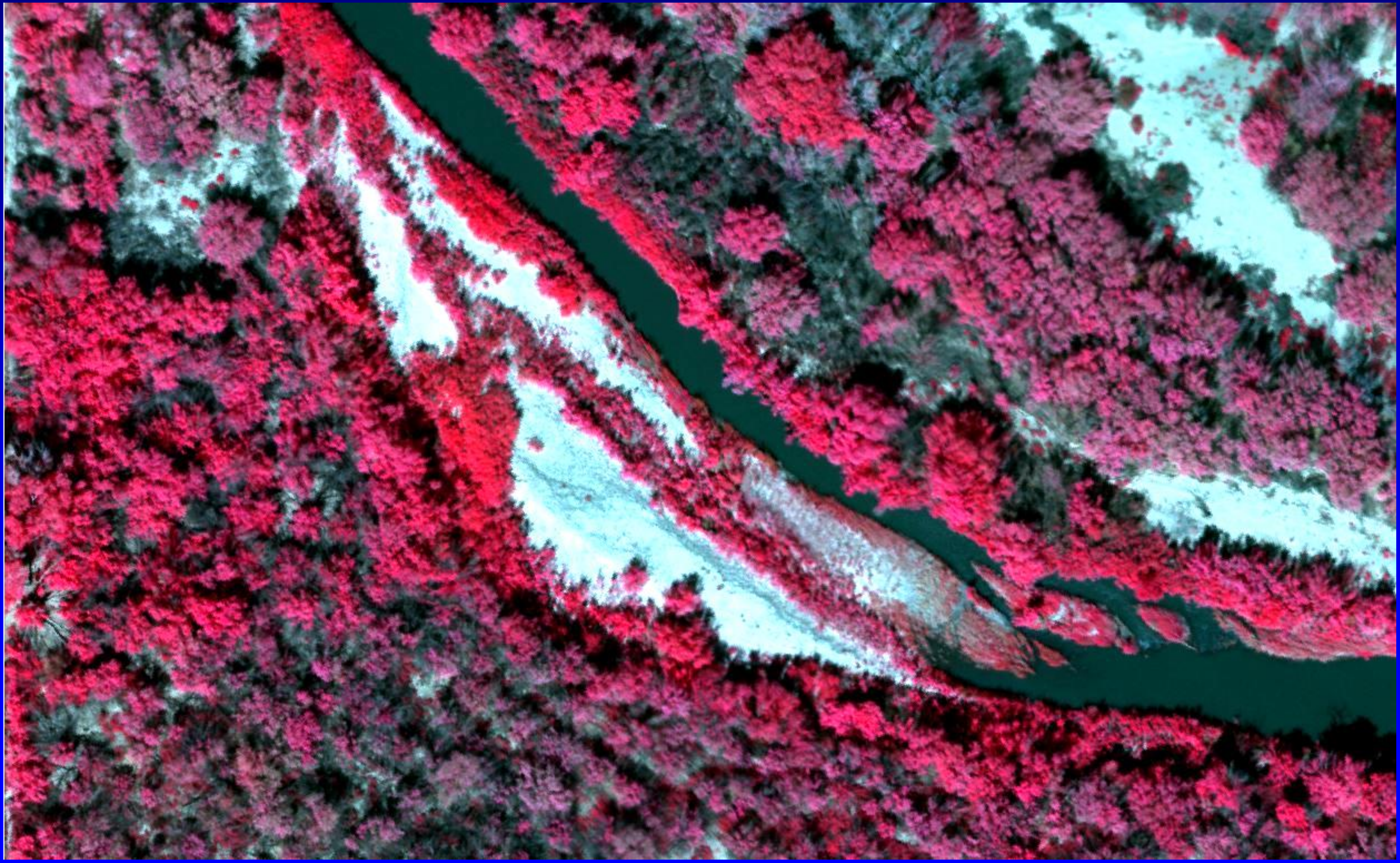
Ground surface TIN and Contours



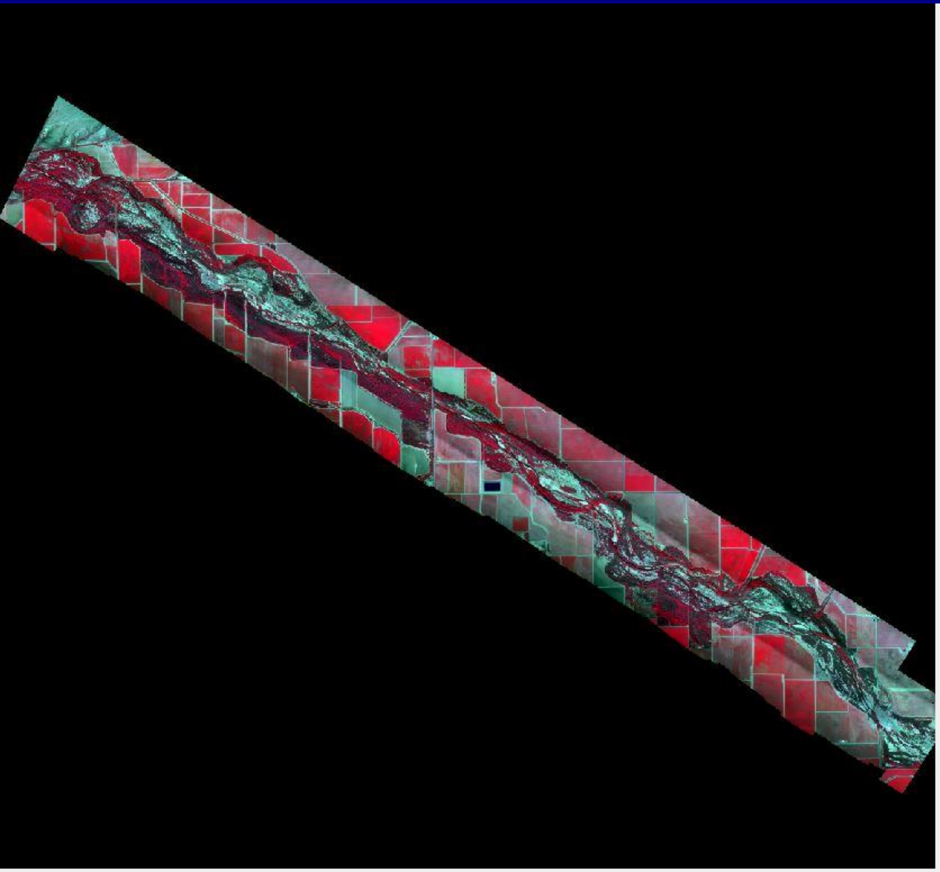


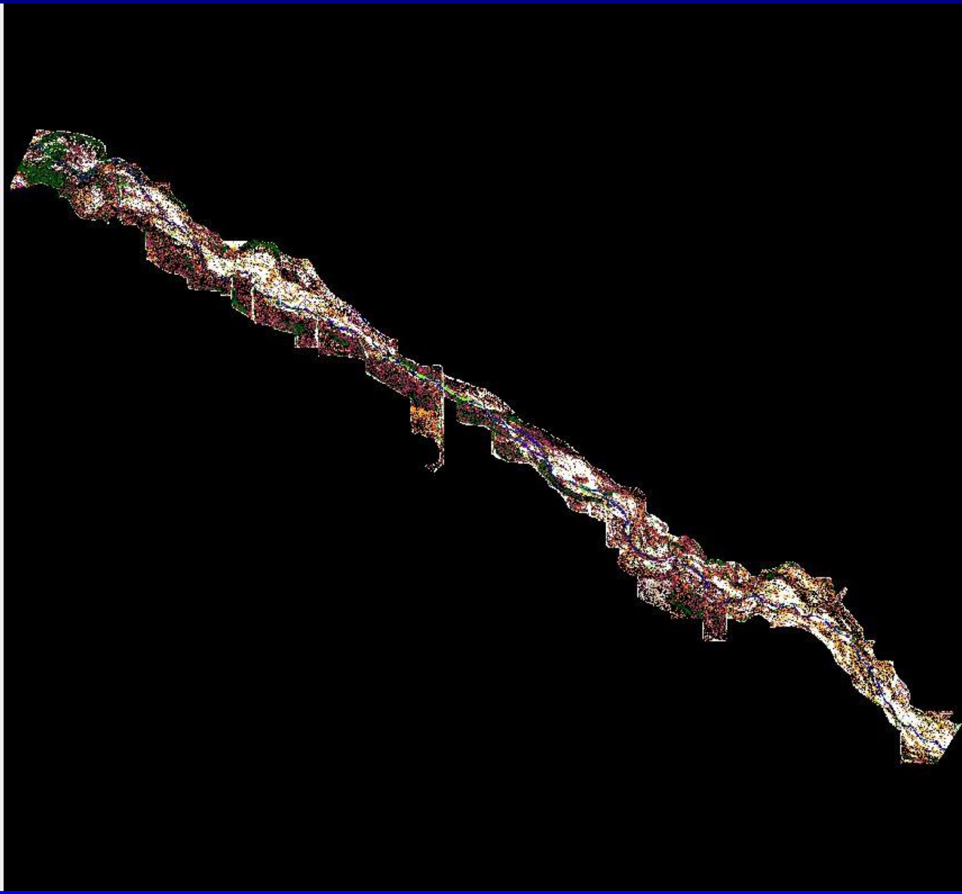
Multispectral Image Detail LASSI 560 Imager

Pixel resolution: 0.16meter (1/2 foot)

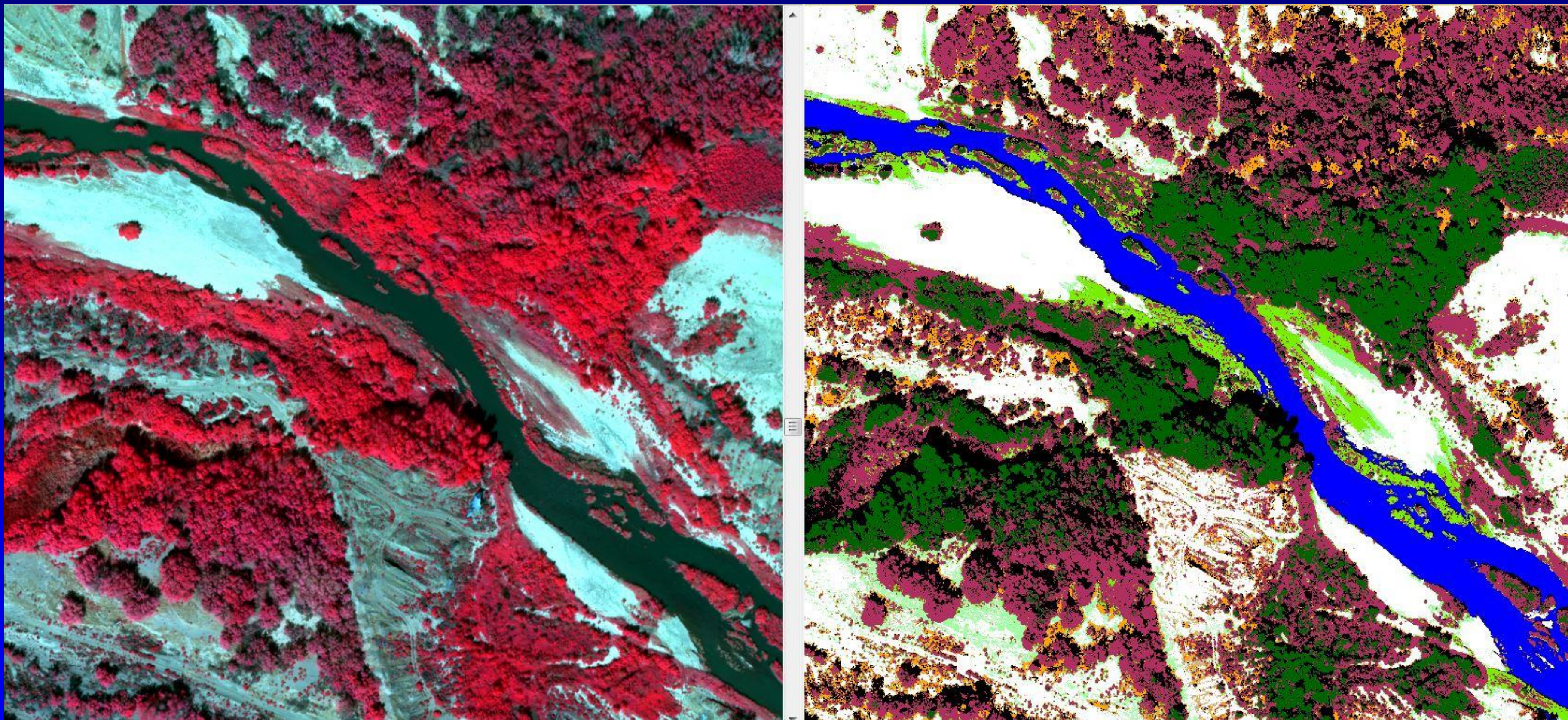


Multispectral Ortho Mosaic of Block AM with Classified Floodplain





Detail of Multispectral Ortho Mosaic of Block AM with Classified Floodplain



1	Water
2	Sand and Rock
3	Bare soil and dry vegetation
4	Defoliated or Dead Salt Cedar
5	Salt Cedar
6	Cottonwood/Gooding Willow
7	Shadow
8	Wetland
9	Upland Vegetation
10	Riparian grasses
11	Mesquite
12	Willow
13	Urban features, roads roof tops

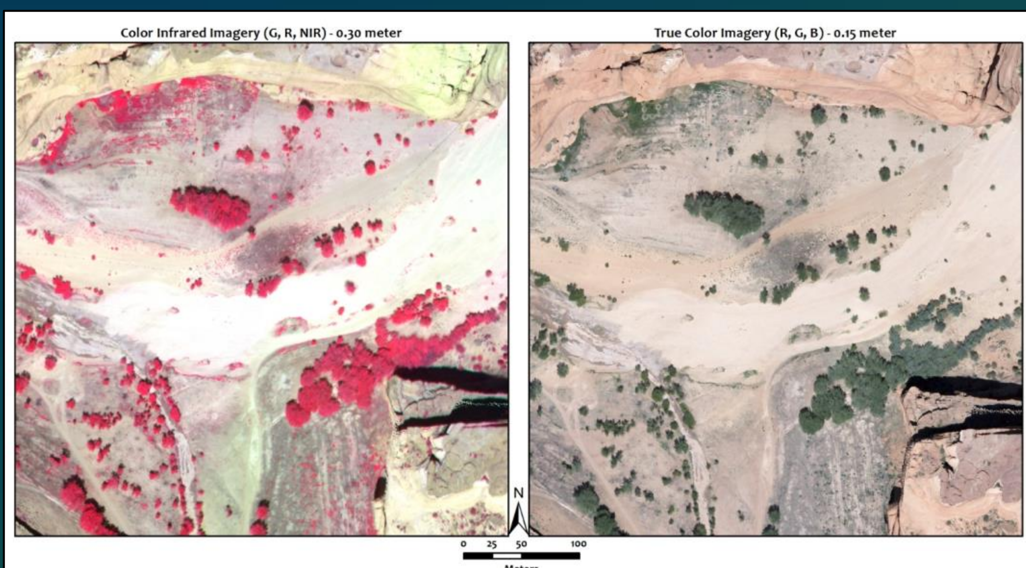
Definiens eCognition

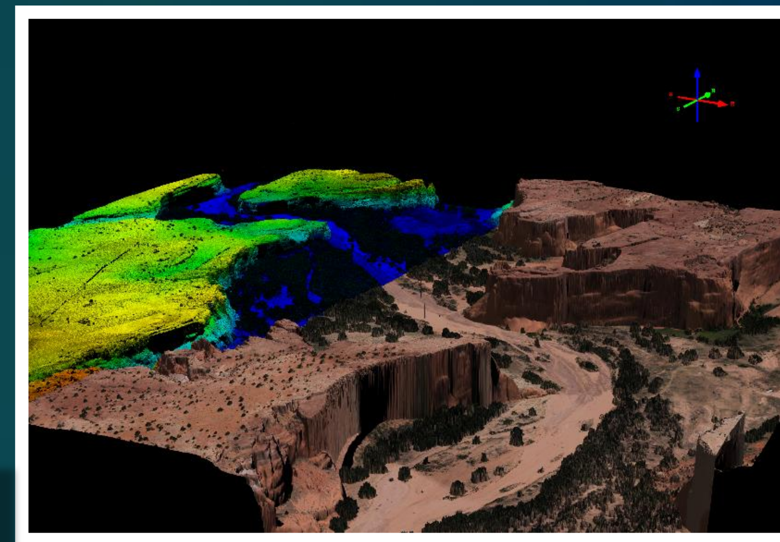
- Definiens was founded in 1994 by Professor Gerd Binning, a German physicist
- Definiens became a commercial enterprise in 2000 with the release of eCognition, the first commercially available OBIA software program
- Headquarters in Munich, Germany
- Definiens eCognition was purchased by Trimble in 2010

- eCognition software enables organizations involved in earth sciences to extract accurate geo-information from any kind of remotely sensed data
- Three product versions:
  - eCognition Developer
  - eCognition Architect
  - eCognition Server

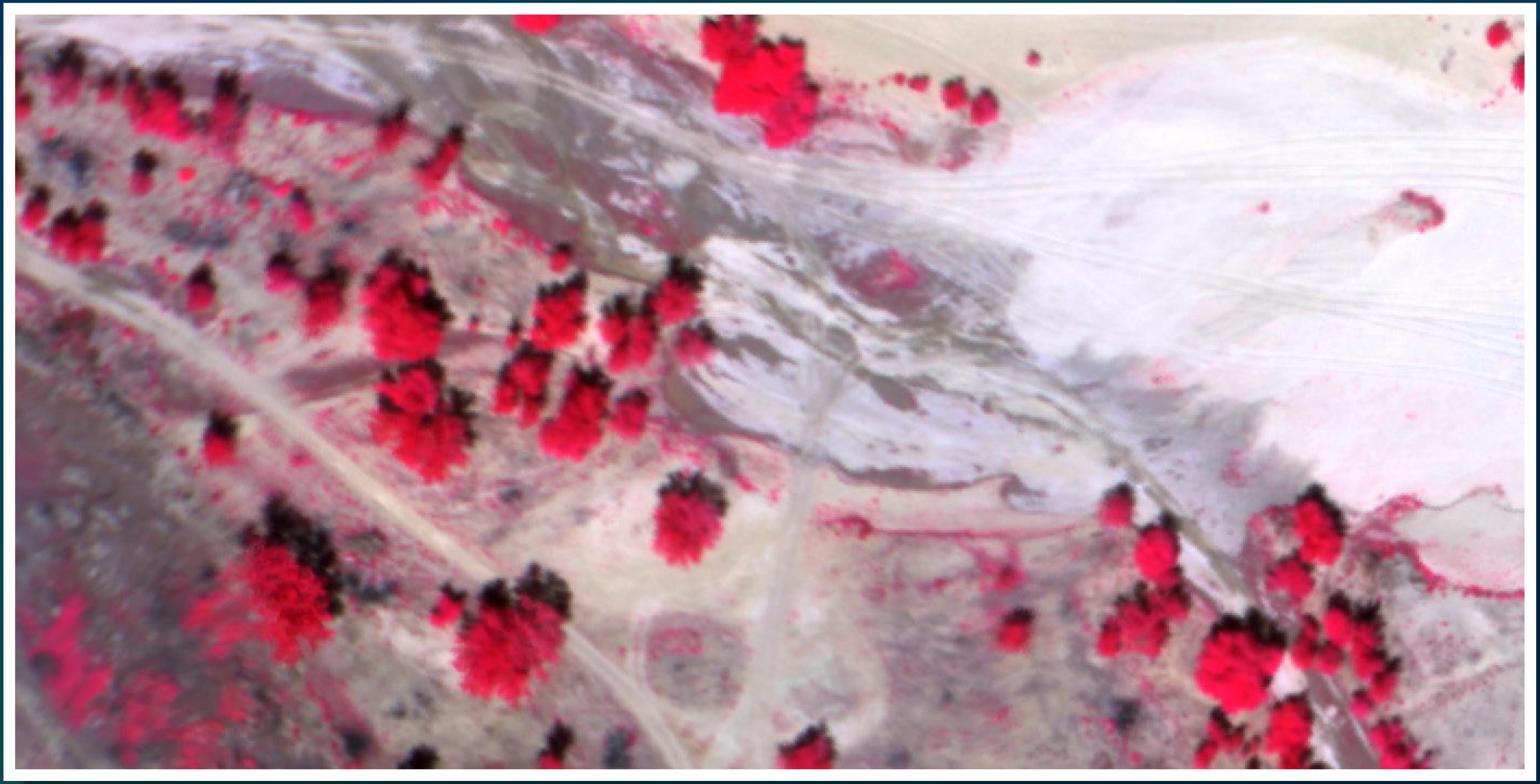
Data – Canyon De Chelly, Arizona

- 15 cm True Color Imagery (R,G,B)
- 30 cm Multispectral (CIR) Imagery (G,R,NIR)
- 0.5 m LiDAR derived DTM and nDSM

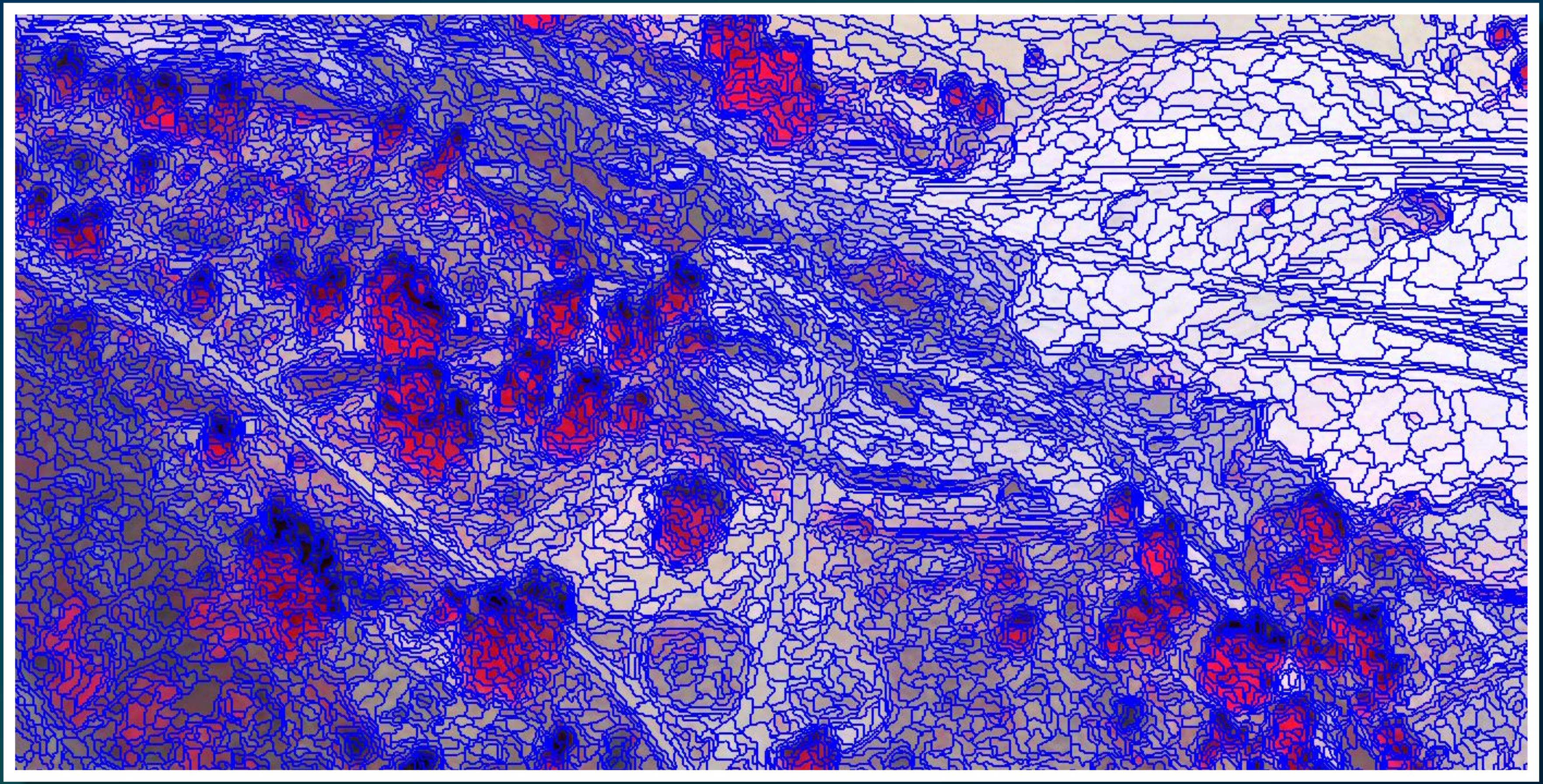




Methods – Canyon De Chelly, Arizona

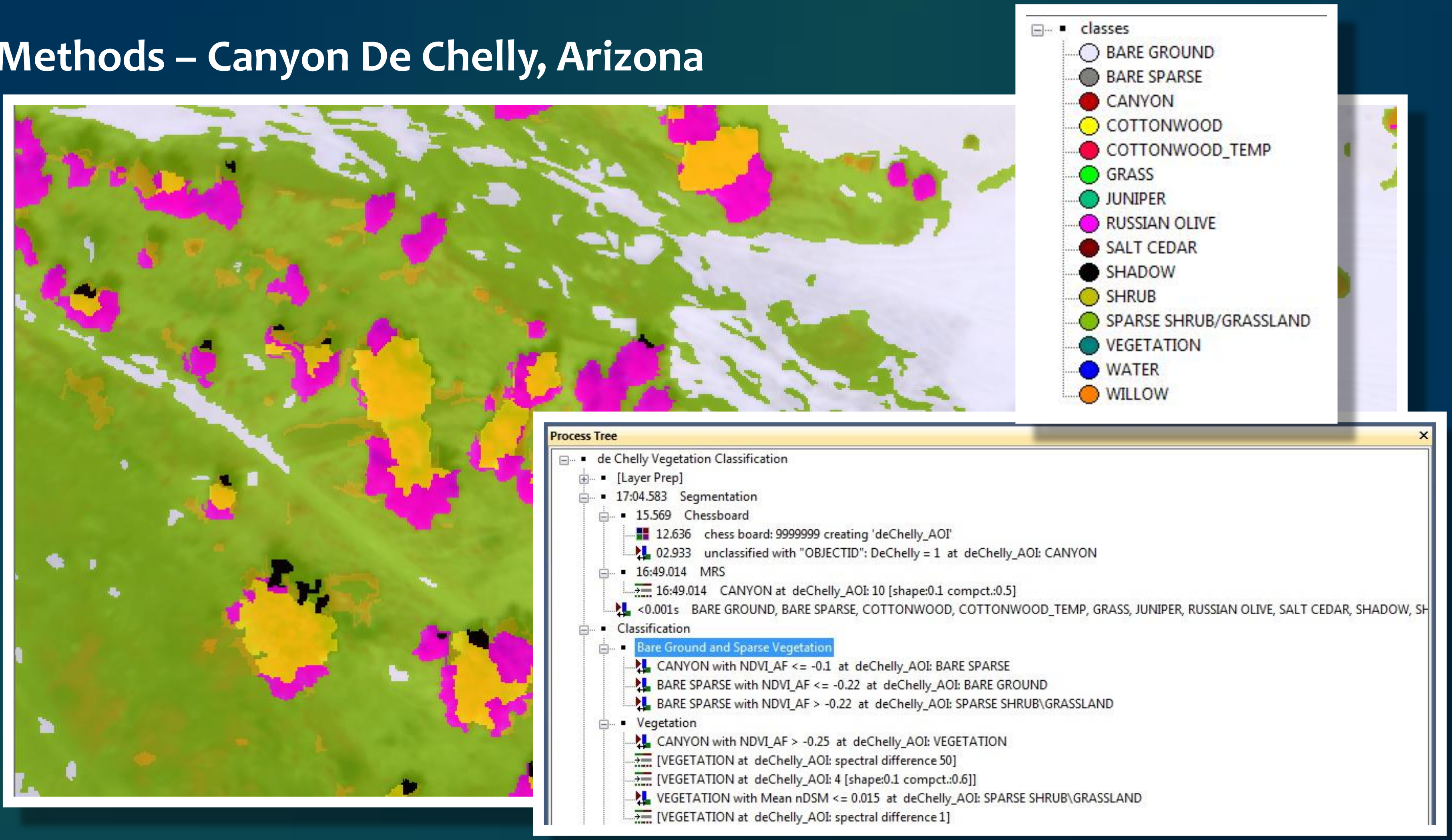


Methods – Canyon De Chelly, Arizona



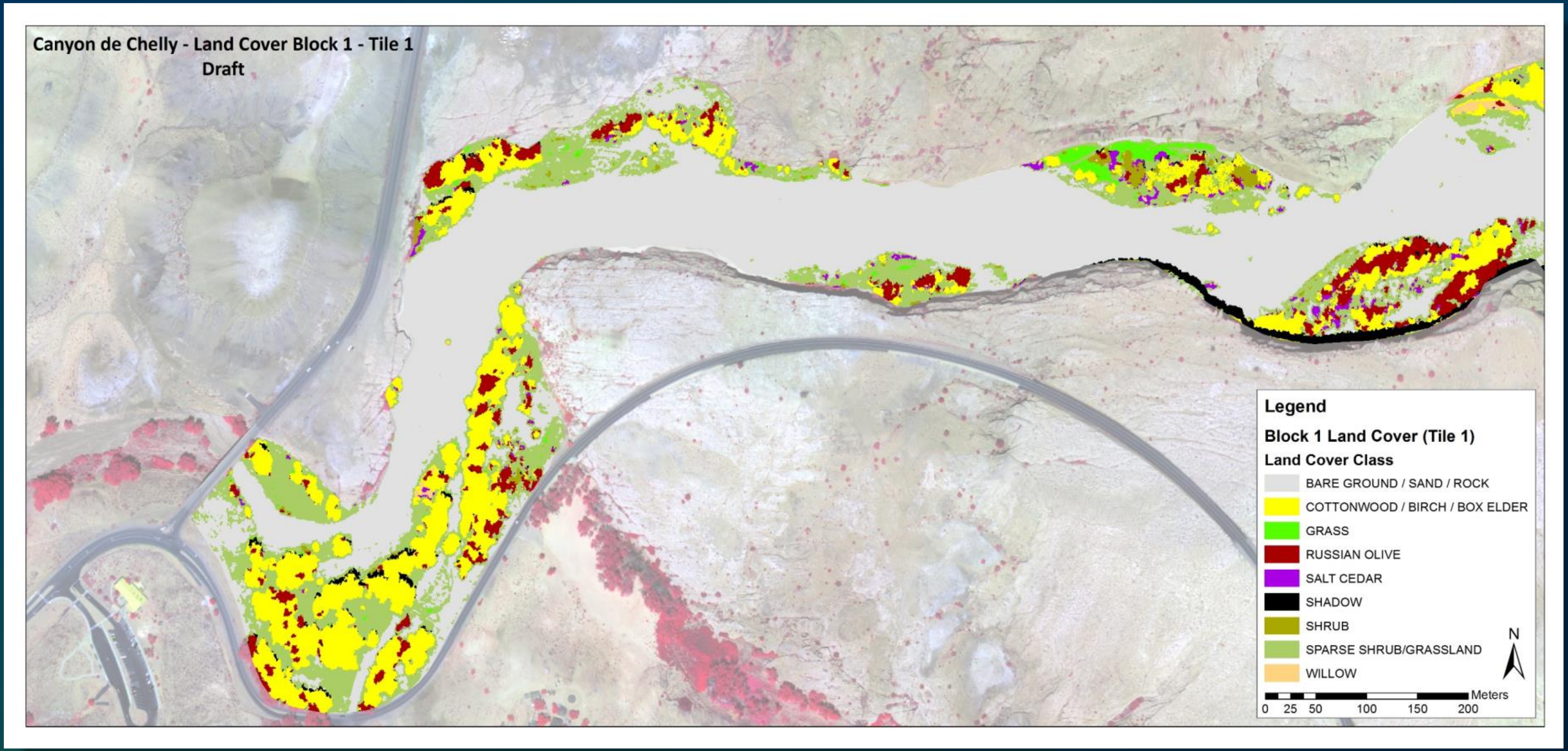
eCognition software for image segmentation and classification

Methods – Canyon De Chelly, Arizona



eCognition rules

Results – Canyon De Chelly, Arizona



RECLAMATION

Managing Water in the West

Evapotranspiration Analysis of Saltcedar and Other Vegetation in the Mojave River Floodplain, 2007 and 2010

Mojave Water Agency Water Supply Management Study Phase 1 Report

U.S. Department of the Interior
Bureau of Reclamation

Mojave Water Agency

Utah State University

Study Overview: Mapping of 94 miles of Mojave River Floodplain

Saltcedar (*Tamarix)*

- **Analyses included:**
  - 2007 and 2010 classification of native and non-native vegetation
  - Vegetation evapotranspiration modeling
  - Lidar elevation map development
  - Groundwater mapping
  - Water evapotranspiration cost calculations
- **Results are presented as a whole and also by Mojave Water Agency Alto, Alto Transition, Centro, and Baja subarea boundaries.**

Mojave Water Agency

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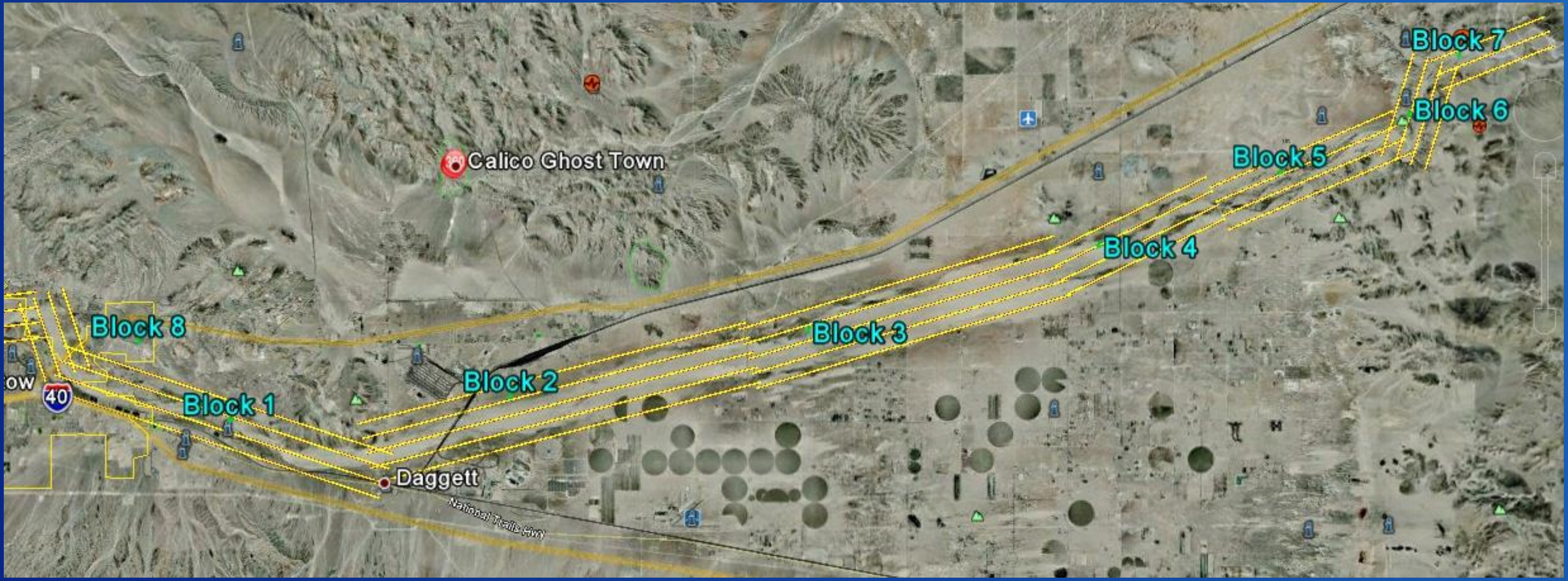
RECLAMATION

Lidar/multispectral flight was planned and flown by blocks of multiple flightlines



Imagery Acquired on June 29 and June 30, 2010 under clear sky conditions

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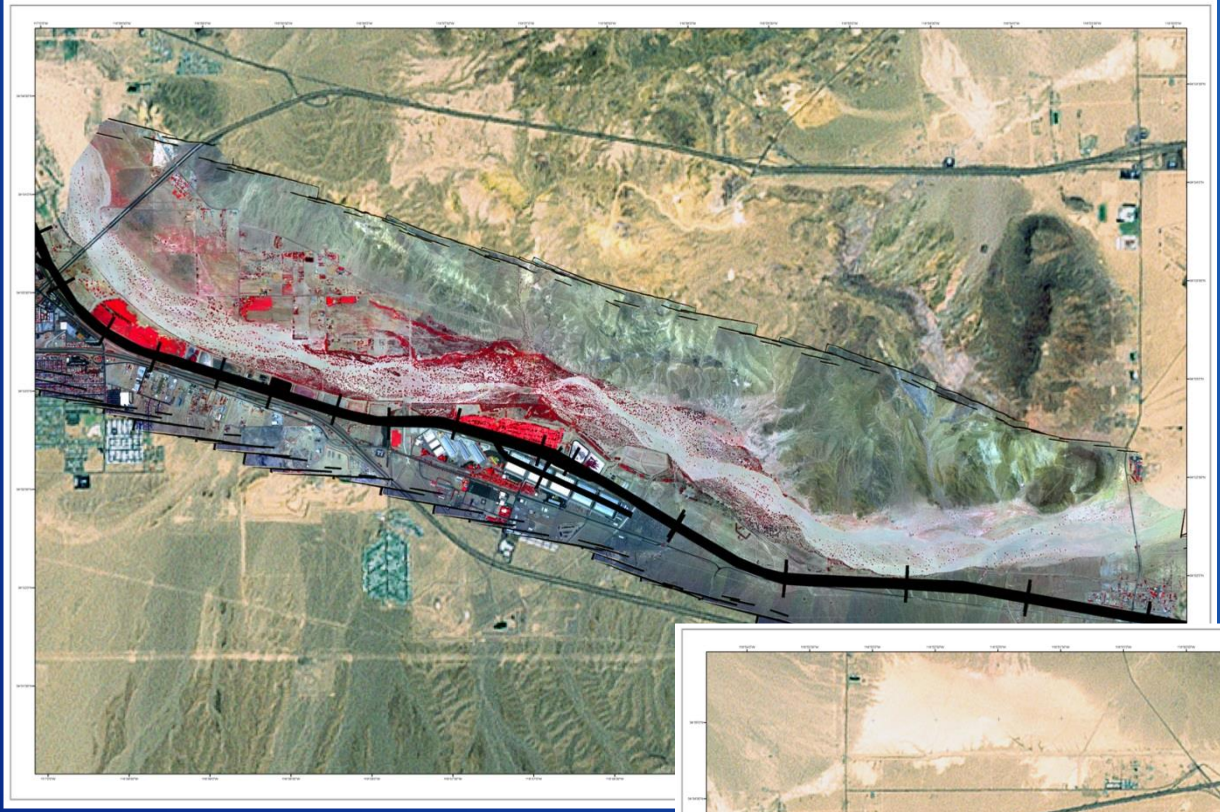
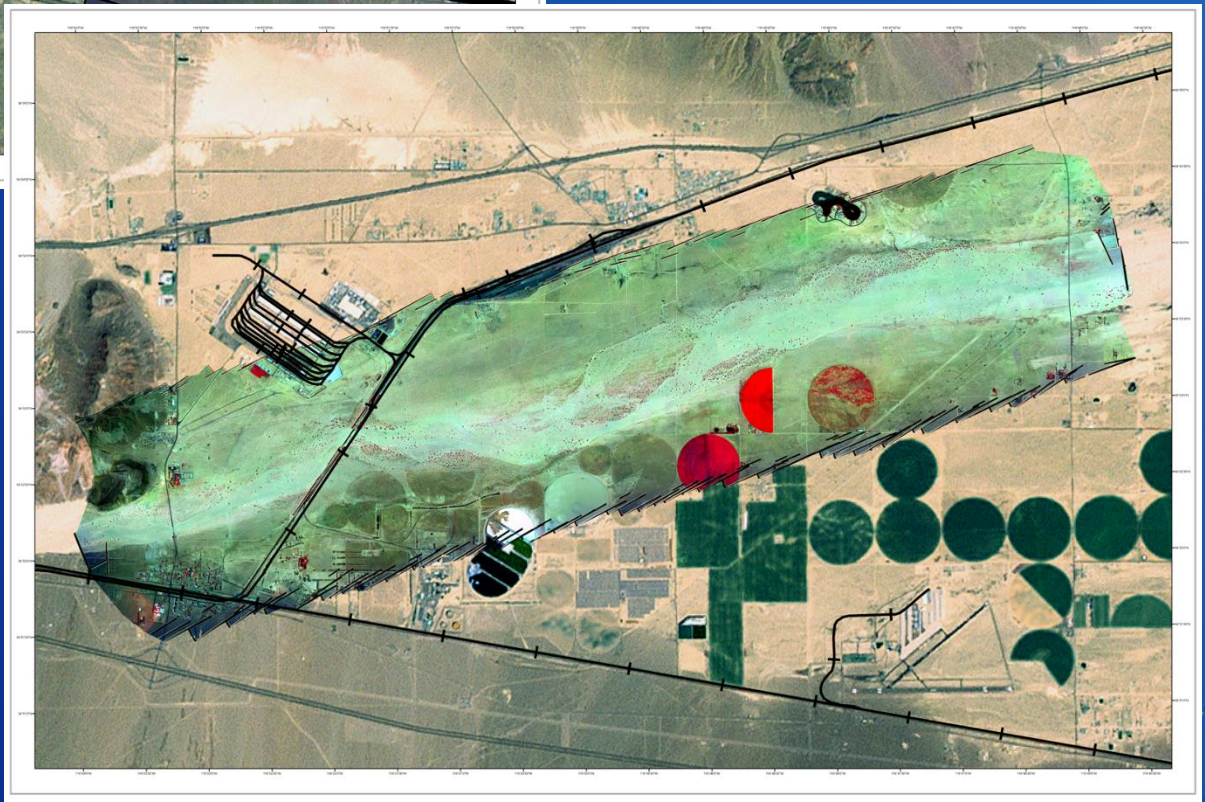
RECLAMATION

Multispectral Ortho Imagery

Block 1 and 2

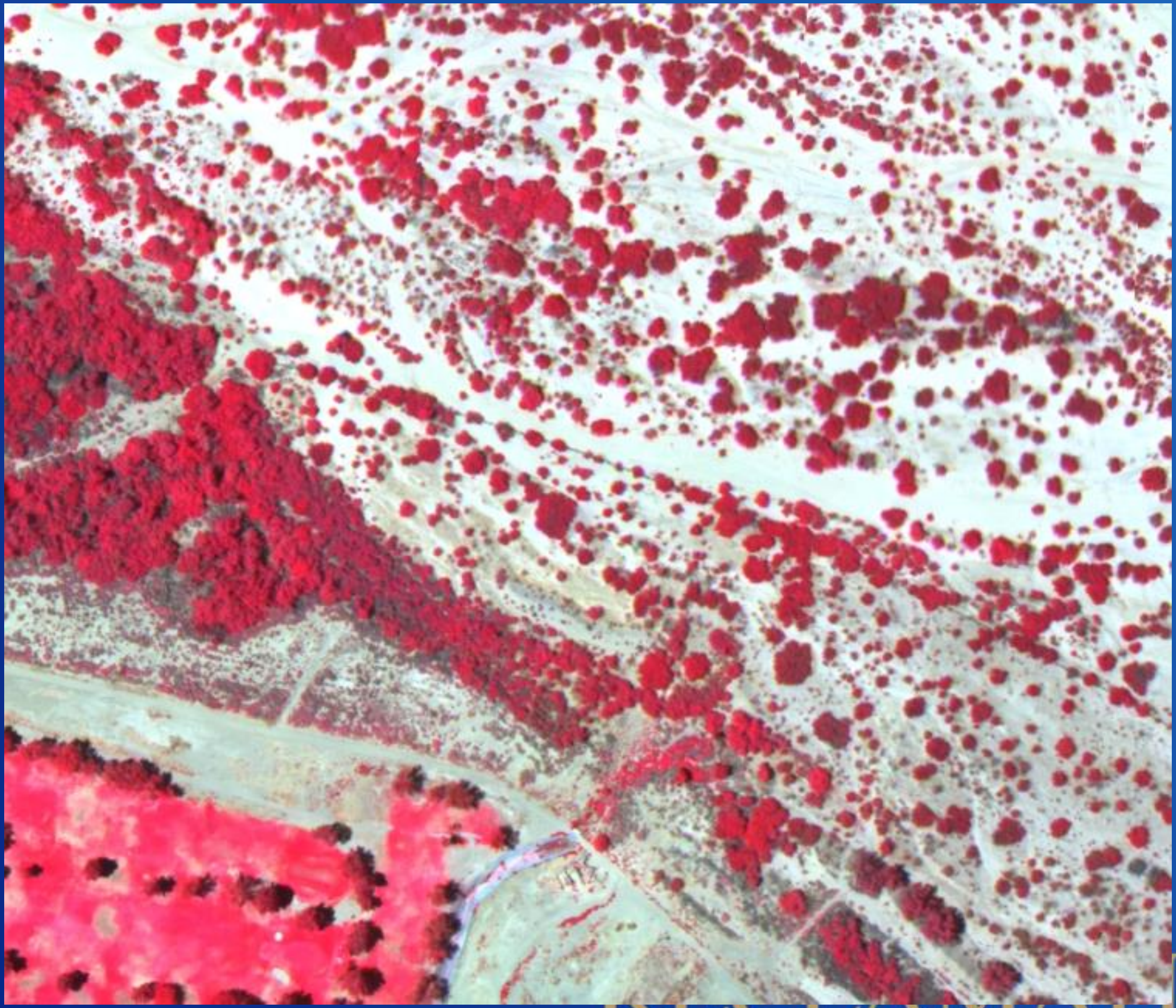




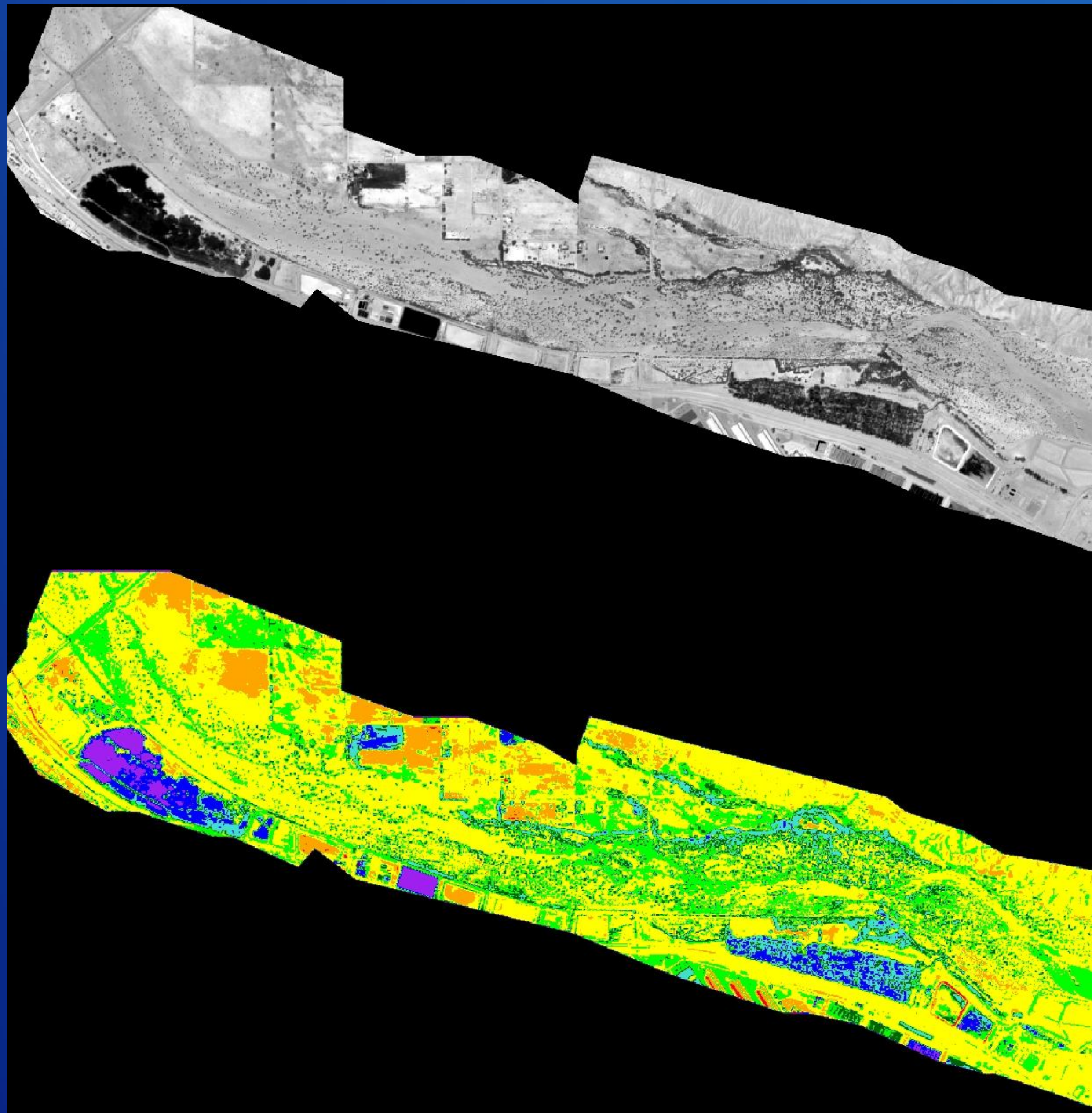
Ortho-rectification using direct geo-referencing with Lidar point cloud data

Multispectral Image Detail

Pixel resolution: 0.35 meter (1 foot)



Thermal infrared Imagery: 1-meter pixel resolution



Temperature

20 – 30 °C

30 – 35 °C

35 – 40 °C

40 – 45°C

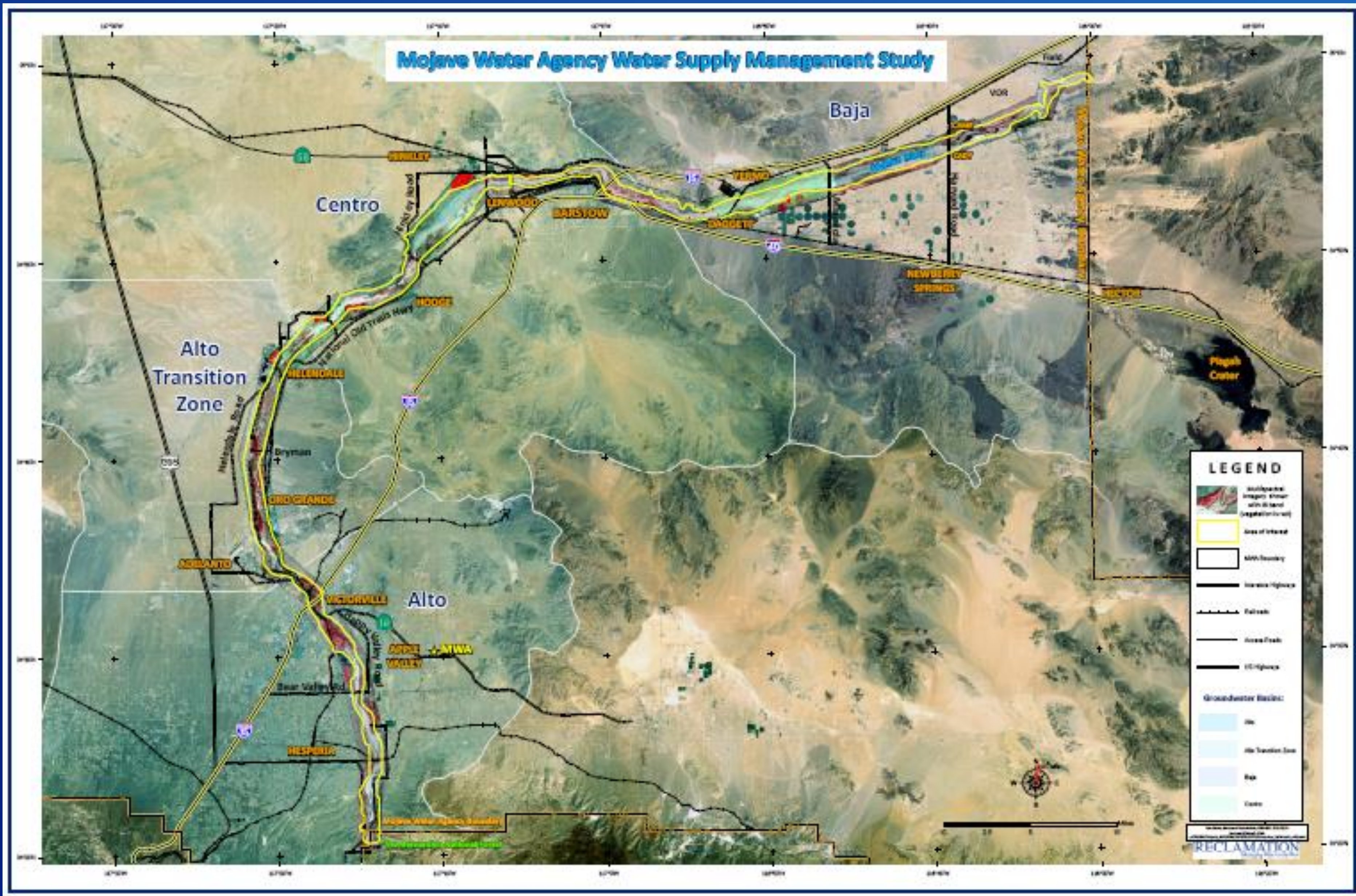
34 – 50 °C

50 – 55 °C

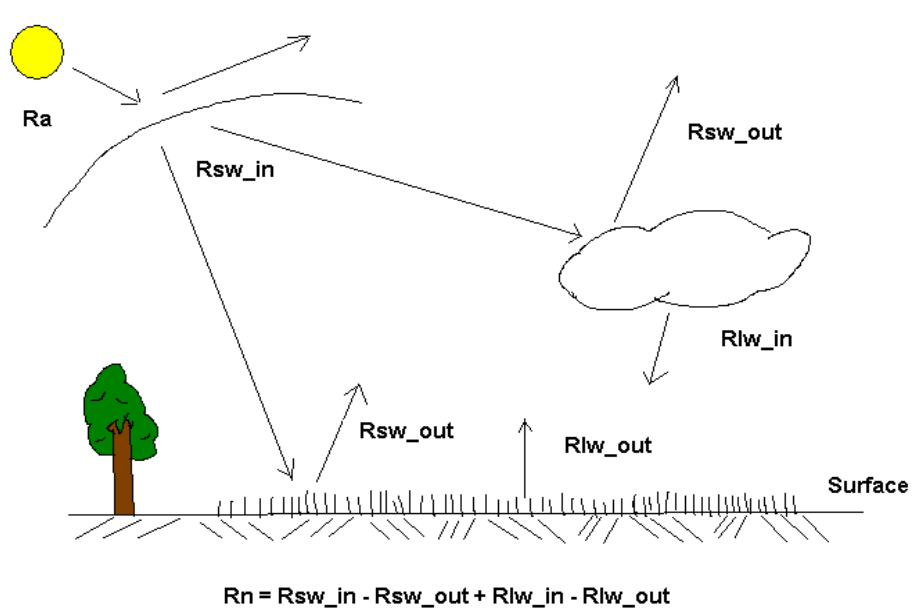
55 – 60 °C

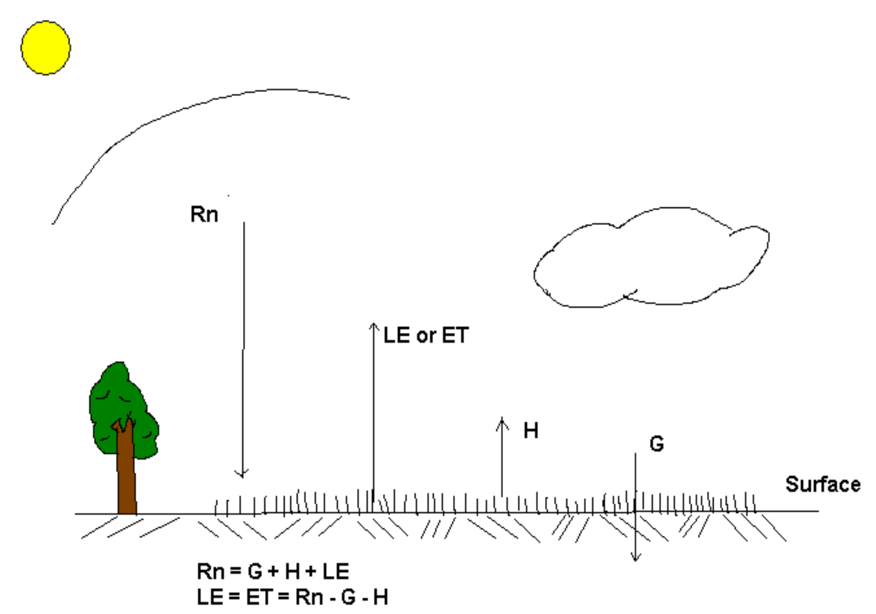
> 60 °C

Analysis Conducted within an Area of Interest (AOI) Polygon



Energy Balance Approaches Used to Estimate Evapotranspiration:





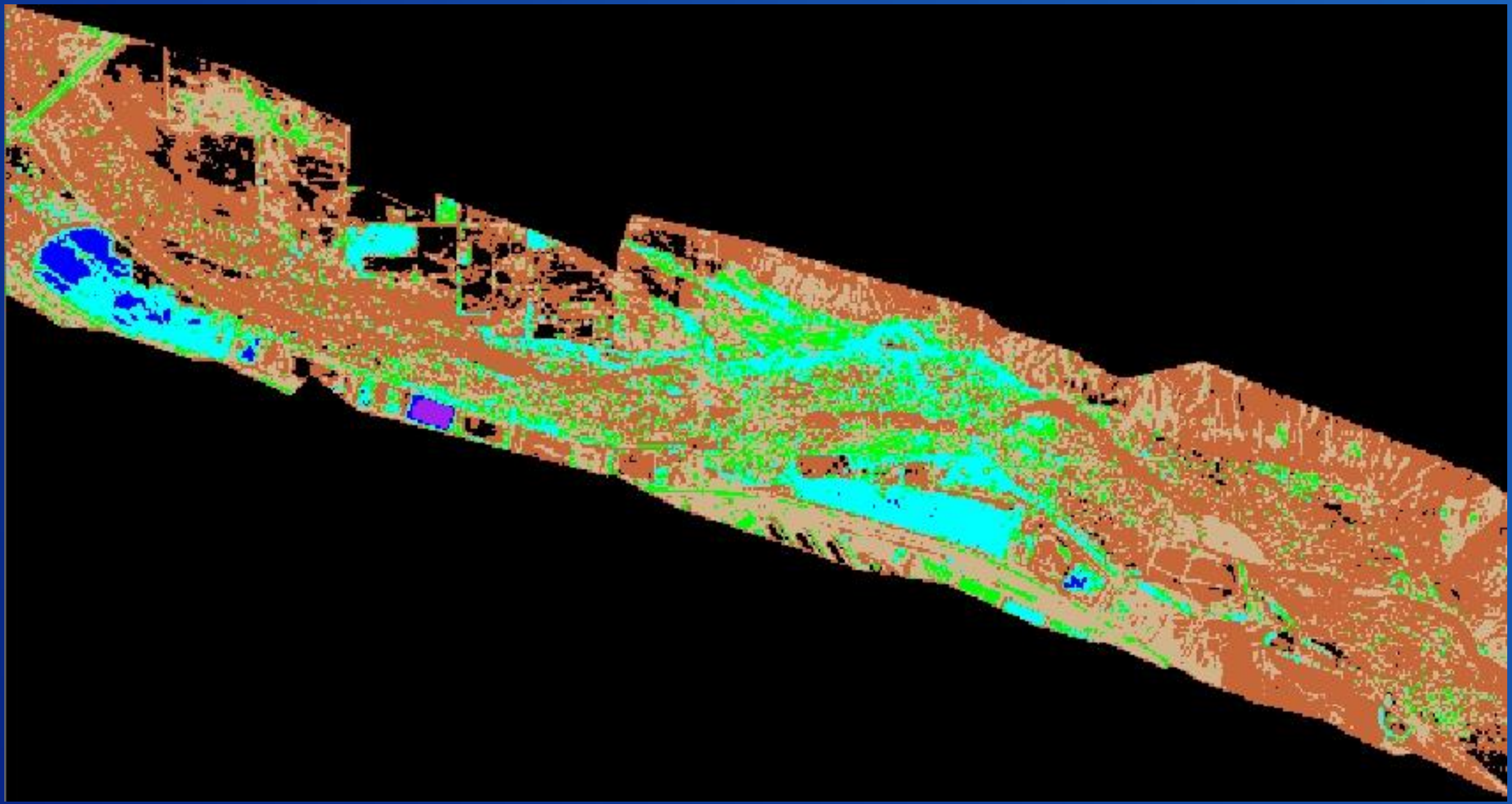
The Two-source model

SEBAL: Surface Energy Balance for Land

“Crop” coefficient model used to extrapolate over the growing season

RECLAMATION

SEBAL ET Results for Block 1



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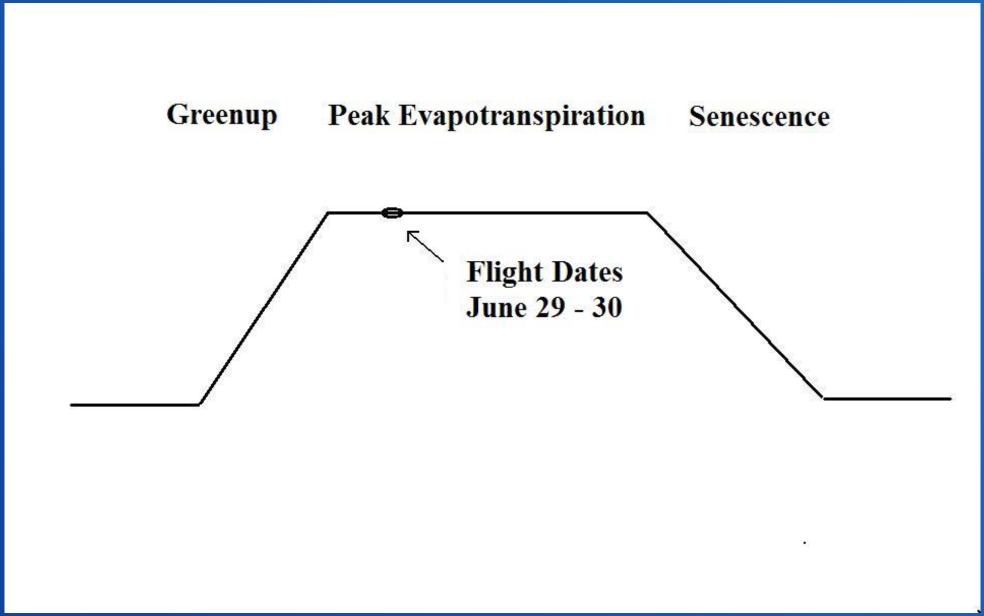
RECLAMATION

Seasonal ET Estimation using ET fractions (crop coefficients) derived from remotely sensed ET

$Kc = ET_a / ET_0$

ET_a = Actual ET from Energy Balance Model

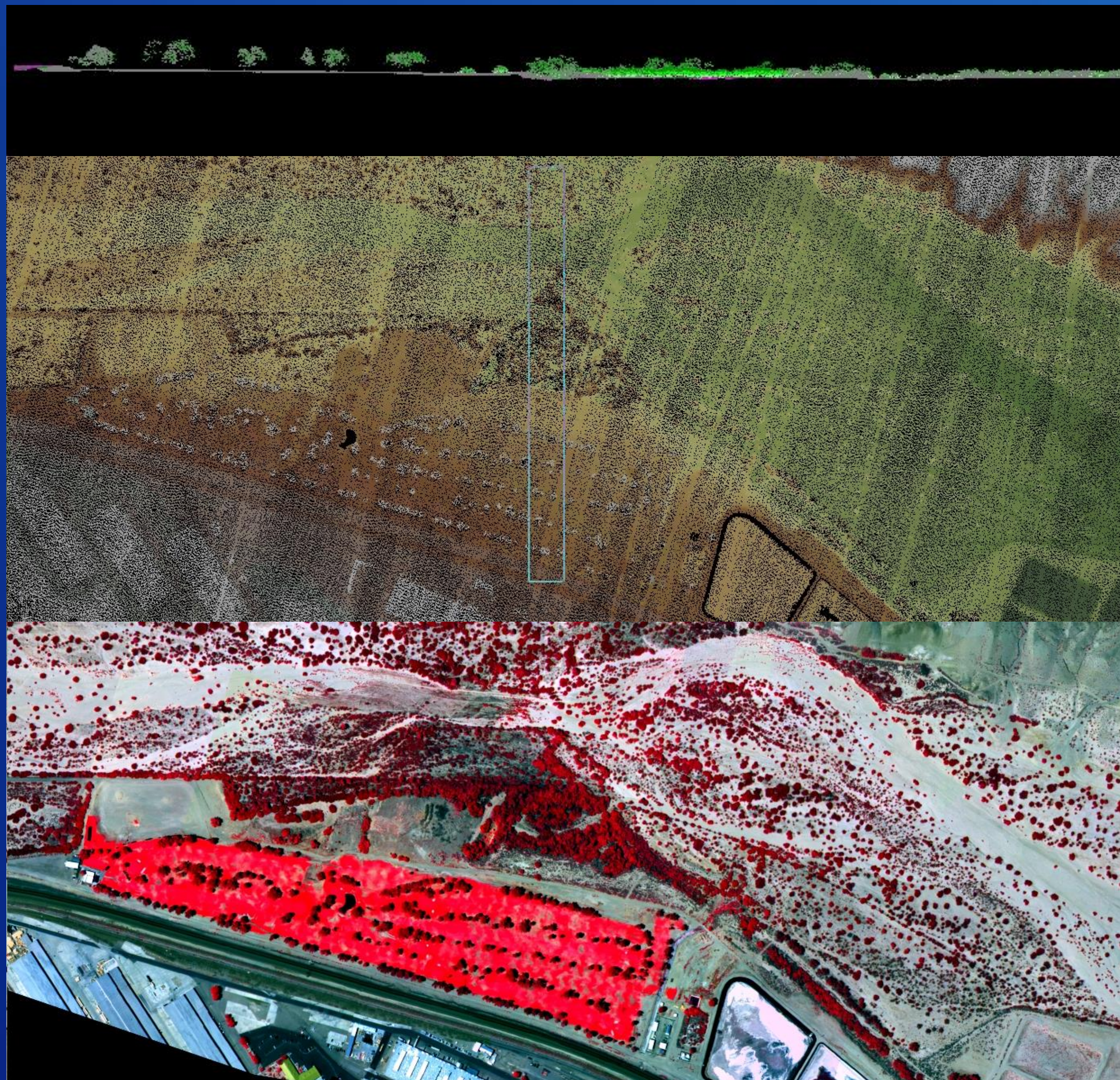
ET_0 = Reference ET from CIMMIS Weather Station



Phenology Dates	Code	Greenup Begins	Peak ET	Senescence Begins	Senescence Ends
Salt Cedar (Tamarisk)	SC	3/1	5/1	9/1	11/1
Mesquite	MS	4/1	5/15	8/1	9/15
Cottonwood	CW	4/1	5/15	9/15	11/1
Desert Scrub	DS	3/1	4/15	7/1	8/1
Decadent Vegetation	VD	4/1	5/15	8/1	9/15
Mesophytes	MP	4/1	5/15	7/1	8/1
Conifer	CO	3/1	5/15	10/1	11/15
Arundo	AR	4/1	6/1	10/1	11/1

RECLAMATION

Classified Lidar point clouds to obtain canopy height at 1-meter grid cells



Mojave Water Agency

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Block 1 Seasonal ET results for Tamarisk using both energy balance models

Table 5. Comparison of seasonal saltcedar ET results (in millimeters of water) for the SEBAL and Two-Source models, Block 1, using modeled canopy height

	2010			2007	
	SEBAL	TSM		SEBAL	TSM
Total ET (mm)					
March to May	107	102		112	107
May to September	533	503		509	480
September to November	230	216		226	212
Total ET (mm)	**870**	**820**		**847**	**799**
Reference ET (grass)	1589	1589		1561	1561

Table 6. Comparison of seasonal saltcedar ET results for the SEBAL and Two-Source models, Block 1, using canopy height derived from lidar

	2010			2007	
	SEBAL	TSM		SEBAL	TSM
Total ET (mm)					
March to May	104	104		109	109
May to September	514	515		491	492
September to November	221	222		217	217
Total ET (mm)	**838**	**840**		**816**	**818**
Reference ET (grass)	1589	1589		1561	1561

The Two-source model was selected for all estimates due to processing speed and expediency

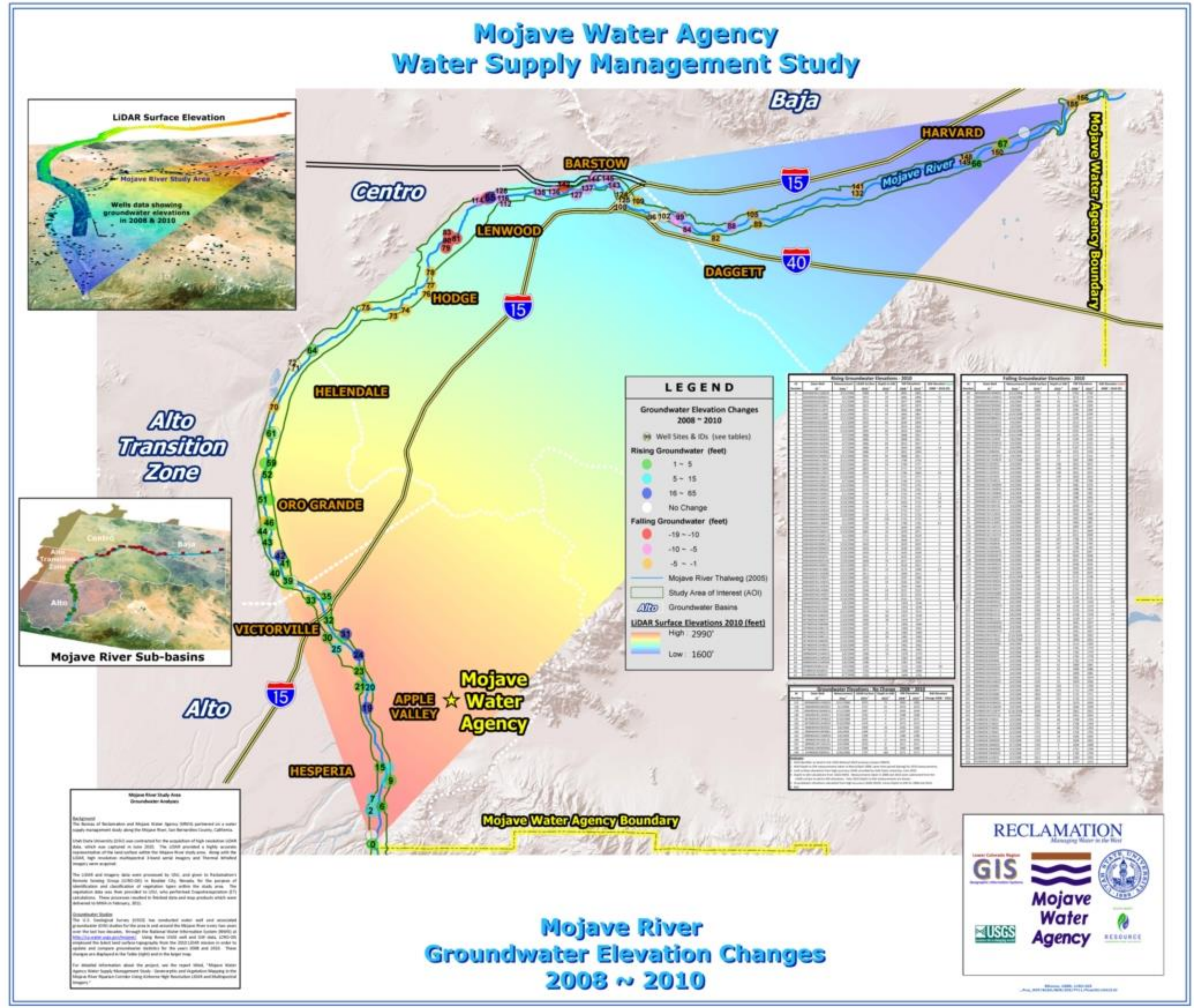
Results for other blocks on downstream side

Table 7. Seasonal saltcedar ET results for the Two-Source model, Block 2 using canopy height derived from lidar.

	2010	2007
Total ET (mm)		
March to May	96	101
May to September	465	445
September to November	198	194
Total ET (mm)	**759**	**740**
Reference ET (grass)	1589	1561

Table 8. Saltcedar crop coefficients by Block in the Baja basin used in the estimation of seasonal ET with Two-Source model

	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6	Block 7
Kc							
Initial Kc (March 1)	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Mean Kc (May to Sept.)	0.53	0.48	0.40	0.48	0.48	0.31	0.28
Late Kc (November 1)	0.15	0.15	0.15	0.15	0.15	0.15	0.15



Mojave Water Agency
Water Supply Management Study
LiDAR Surface Elevation
Mojave River Study Area
Wells data showing groundwater elevations in 2008 & 2010
Baja
Centro
HARVARD
BARSTOW
LENWOOD
DAGGETT
HODGE
HELENDALE
ORO GRANDE
VICTORVILLE
APPLE VALLEY
HESPERIA
Mojave River
Alto Transition Zone
Alto
Mojave Water Agency
Mojave Water Agency Boundary
Mojave River Sub-basins
LEGEND
Groundwater Elevation Changes 2008 ~ 2010
Well Sites & IDs (see tables)
Rising Groundwater (feet)
1 ~ 5
5 ~ 15
16 ~ 65
No Change
Falling Groundwater (feet)
-19 ~ -10
-10 ~ -5
-5 ~ -1
Mojave River Thalweg (2005)
Study Area of Interest (AOI)
Groundwater Basins
LiDAR Surface Elevations 2010 (feet)
High : 2990'
Low : 1600'
Mojave River Study Area Groundwater Analysis
RECLAMATION
Managing Water in the West
GIS
USGS
Mojave Water Agency
Mojave River
Groundwater Elevation Changes
2008 ~ 2010

Table 9. ET fraction of different vegetation types for the 4 groundwater subareas.

	ALTO							
	SC	DS	CW	MS	VD	MP	CO	AR
Initial Greenup Kc	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Peak Kc	0.49	0.34	0.71	0.36	0.33	0.56	0.36	0.4
Final Senescence Kc	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
	ALTO TRANSITION							
	SC	DS	CW	MS	VD	MP	CO	AR
Initial Greenup Kc	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Peak Kc	0.5	0.27	0.63	0.23	0.33	0.49	0.35	0.41
Final Senescence Kc	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
	CENTRO							
	SC	DS	CW	MS	VD	MP	CO	AR
Initial Greenup Kc	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Peak Kc	0.48	0.23	0.62	0.42	0.25	0.39	0.32	0.66
Final Senescence Kc	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
	BAJA							
	SC	DS	CW	MS	VD	MP	CO	AR
Initial Greenup Kc	0.15	0.15	0.15	0.15	0.15	0.15	0	0
Peak Kc	0.47	0.25	0.56	0.27	0.24	0.43	0	0
Final Senescence Kc	0.15	0.15	0.15	0.15	0.15	0.15	0	0

Table 19. Evapotranspiration and estimated seasonal water use by saltcedar in the Alto subarea during 2007 and 2010 seasons.

Year	2007	2010
Initial Greenup Kc	0.15	0.15
Peak Kc	0.48	0.48
Final Senescence Kc	0.15	0.15
Total Area (acres)	85	2.5
ET Greenup Period (mm)	101	96
ET Peak Period (mm)	444	465
ET Senescence Period (mm)	194	194
Total Seasonal ET (mm)	739	755
Volume (m3)	253,639	7,546
Volume (gallons)	67,004,350	1,993,490
acre-feet	210	6

Table 13. Evapotranspiration and estimated seasonal water use by saltcedar in the Centro subarea during 2007 and 2010 seasons.

Year	2007	2010
Initial Greenup Kc	0.15	0.15
Peak Kc	0.50	0.50
Final Senescence Kc	0.15	0.15
Total Area (acres)	751	633
ET Greenup Period (mm)	104	99
ET Peak Period (mm)	465	487
ET Senescence Period (mm)	204	204
Total Seasonal ET (mm)	774	790
Volume (m3)	2,351,576	2,023,410
Volume (gallons)	621,220,566	534,528,276
acre-feet	1,864	1,643

RECLAMATION

Conclusions and remarks

- Airborne imagery is a useful tool for estimating evapotranspiration of natural and agricultural vegetation with high spatial variability

- Intermediate scale between ground and satellite measurements

- Use of these systems in an international context will depend on the needs for a country agency or private sector for data beyond what present satellite systems can offer